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THE DYNAMICS OF STRUCTURAL CHANGES IN THE DEFENSE INDUSTRIES

Herman Stekler
Robert E. Kuenne
Leland Strom

January 1981

Prepared for

Office of the Assistant Secretary of Defense
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INSTITUTE FOR DEFENSE ANALYSES
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This paper analyzes the effects that technological change might have upon the price of weapon systems. It also examines and evaluates the existing cost estimating methodologies to determine whether they are appropriate in the presence of dynamic structural changes. A methodology for relating production processes to costs and cost estimating methodologies is developed and then applied to fighter aircraft. Finally, recommendations for developing cost estimating techniques that accommodate technological change are presented.

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PREFACE

This paper was prepared by the Institute for Defense Analyses for the Office of the Assistant Secretary of Defense (OASD), Planning, Analysis and Evaluation (PA&E) under Contract MDA 903-79-C-0320, Task Order No. PA&E 133 issued March 1980 and amended April 1981.

The research conducted under this task deals with issues involved in analyzing the effects which structural changes in the defense industries have upon the prices of weapon systems.

A final draft report was submitted to OASD/PA&E in December 1980 per the task schedule. Following formal PA&E Project Office review, and Security Review, this report was submitted for publication and is issued in fulfillment of the contract.

FOREWORD

This paper examines the dynamics of structural changes in the defense industries. It was prepared under contract to the Office of the Assistant Secretary of Defense (Program Analysis and Evaluation). OASD/PA&E is concerned both with the factors (such as changes in technology and industry structure) which affect the prices of weapon systems, and the methodology which is used to estimate the costs of procuring those systems.

This paper analyzes the effects that technological change might have upon the price of weapon systems. It also examines and evaluates the existing cost estimating methodologies to determine whether they are appropriate in the presence of dynamic structural changes. A methodology for relating production processes to costs and cost estimating methodologies is developed and then applied to fighter aircraft. Finally, recommendations for developing cost estimating techniques that accommodate technological change are presented.

ACKNOWLEDGMENTS

We wish to thank Lt. Col. Douglas Fisher for developing the data which are analyzed in Chapter II. Mr. Thomas August and the executives of the McDonnell-Douglas Corporation worked intensively on our behalf to prepare the data used in Chapter VII. This paper has benefited from the incisive comments of Prof. Lee E. Preston, Prof. Fred Scherer, Dr. James Bell and Dr. Harry Williams. The thoughtful editing of Eileen Doherty eliminated the stylistic havoc which we were about to inflict upon the English language and upon the reader. Finally, this paper could not have been completed without the professional dedication of Ms. Bernie Aylor who typed the final versions.

CONTENTS

APPENDIXES

FIGURES

TABLES

TABLES (Continued)

EXECUTIVE SUMMARY

Previous economic analyses of the defense industries have developed several types of functional relationships between the cumulative output of a weapon system and its unit price or cost. These functions assume that other factors, such as the yearly rate of production of the particular item and the rate of technological change within that particular sector of the defense industry, would not affect this relationship. Nevertheless, even after adjusting for inflation, defense cost analysts have observed that the prices paid for many defense systems have exceeded the estimates which were derived from these cost relationships. It is possible that these cost relationships no longer are valid, and that structural changes which have occurred in the defense industries may have contributed to this reduction in accuracy.

This study examines one set of structural changes, those attributable to technological factors, and analyzes the effects of these changes upon the cost relationships. The cost relationships are affected because technological changes, which are the result either of quality improvements or alterations of manufacturing techniques, affect production relationships. In turn costs are affected, and valid cost estimating techniques must take these changes into account.

The defense sector of the economy consists of many industries, and it would not have been feasible to analyze the technological changes of each industry. This study, therefore, focuses upon the technological changes which have occurred in the military aircraft industry and considers the impact that these changes have had on airframe cost estimating relationships.

Ideally, the costs of a system, such as an airframe, would be estimated from the inputs required to produce that system. Unfortunately, some cost estimates are usually required before the configurations of a system have been established, in which case it is impossible to determine the inputs required; costs therefore must be estimated in some other manner.

In those cases where the values of the required inputs cannot be determined, an entirely different methodology for estimating costs has been developed. The costs of particular systems are determined from parametric cost estimating relationships (CERs). These equations relate the costs of specific systems to key physical or performance characteristics of the systems. Although these CERs have been utilized for two decades, there has been no previous systematic evaluation of their forecasting accuracy.

An evaluation of a preferred airframe CER is presented in Chapter II. The purpose of such an evaluation is not to critique the particular equation, but to determine whether a CER which does not contain an explicit technological change variable, such as the complexity of the system, might exhibit any forecasting biases. The evaluation specifically determines how well the preferred airframe CER predicts outside the sample and whether the coefficients in the estimated equation remain stable when additional data points are included in the sample.

The results indicate that there are systematic biases in the engineering and tooling hours estimates. In addition, it appears that at least some of the CER equations do not have stable coefficients. These findings suggest that some factor has affected the accuracy of the CERs; this factor might be the technological changes which affected the process by which airframes are produced. These changes may have resulted from the substitution of one type of labor for another, the introduction of labor saving capital, the use of new materials or the effect of technological change in general.

Given the reduction in accuracy of the CERs, we found it necessary to develop the conditions under which CERs might yield meaningful cost predictions. These conditions can also explain how technological changes might cause the existing CERs to yield less meaningful estimates.

It should be noted that the existing learning curves and CERs do not explicitly incorporate any information about the factors of production, technological change, or the interaction between production techniques, quality changes and technological changes. This is despite the fact that the aforementioned economic processes determine costs and learning. However, the analysis of Chapter III shows that the learning curve used in cost analysis *is* related to the cost functions obtained from cost minimizing procedures applied to production functions. The learning curves can also be directly related to production functions which include the various types of technological change.

Production functions and CERs are also related, but the relationship is complex because CERs estimate costs from product qualities. The production function must be modified to analyze the relationship between product characteristics and factor inputs and costs. Our analysis shows that CERs might shift proportionally in response to quality changes if three crucial assumptions hold:

- Product quality changes do not affect factor proportions (i.e. the ratios of labor, capital, and materials relative to each other).

- The technology used to manufacture the product does not change when system characteristics are altered.
- The rate of learning remains constant.

Even under these circumstances, *we cannot conclude that the cost estimates obtained directly from CERs and those derived from production functions incorporating qualities must be identical.* Moreover, when the three assumptions are relaxed, there is even less likelihood that the two estimates will coincide.

Since technological changes must be considered in determining the costs of weapon systems, it is necessary to examine the manner in which the production processes are influenced. The production costs of a system may be affected by two types of technological change: changes either in the methods of production or in the quality (characteristics) of the system. It is theoretically possible to separate these two effects, but it has proven difficult to empirically divide the observed results into the two distinct components. It has been especially difficult to analyze these changes for products such as aircraft which have multi-dimensional characteristics.

Our empirical analysis divides the technological changes which occurred in the fighter aircraft industry into the two components. The first component, the increasing complexity of military aircraft, is measured (1) by the ratio of research and development costs to total procurement costs, and (2) by the number of electronic components contained within various weapon systems. For example, Table S-1 shows that non-recurring costs as a percentage of total costs are higher on average for later model aircraft than they were for earlier aircraft; aircraft complexity, which is still a relatively intangible concept, has increased with time. Direct measures of combat aircraft performance such as max speed, payload, range, etc. clearly show (Chapter V, p. 57) that the aircraft were

Table S-1. TOTAL, NON-RECURRING, AND RECURRING COSTS OF THE FIRST 100 AIRFRAMES OF VARIOUS FIGHTER AND ATTACK AIRCRAFT

Air-Craft	Total	Non-Recurring Costs (Millions of 1970 $)	Recurring Costs	Non-Recurring Costs as a Percentage of Total Costs
F-84	96.7	10.7	86.0	11.1
F-86	103.7	16.7	87.0	16.1
F-86D	159.2	34.2	125.0	21.5
F-3	293.7	63.7	230.0	21.7
F-89	231.4	17.4	214.0	7.5
A-3	371.	34.0	337.0	9.2
F-100	209.2	59.2	150.0	28.3
F-101	421	81.0	340.0	19.2
A-4	n.a.	n.a.	173.0	n.a.
F-102	554.	184.0	370.0	33.2
F-104	257.5	47.5	210.0	18.4
F-105	683	153	530.0	22.4
F-106	590	200	390.0	33.9
A-5	722	222	500.0	30.7
F-4	606	146	460.0	24.1
A-6	n.a.	n.a.	215.0	n.a.
A-7A/B	158	35	123.0	22.2
F-111	1395.9	395.9	1000.0	28.4
F-14	899	269	630.0	30.0

Source: J.W. Noah, J.M. Daniels, C.F. Day, and H.L. Eskew, *Estimating Aircraft Acquisition Costs by Parametric Method*, J. Watson Noah Associates, Alexandria, Va., September 1973, FR-103-USN, pp. 33-34.

designed to fly faster and higher or to carry heavier payloads for a longer distance. The aerodynamic design changes which produced some of the observed performance characteristics sometimes required changes in manufacturing technology and/or production inputs.

The second component of technological change, alterations in manufacturing technology, is analyzed by examining the new materials, new types of capital equipment, and different manufacturing techniques which have been introduced and the changing characteristics of the labor force which is utilized. One major manufacturing advance in the military aircraft industry has been the introduction of new materials from which the structural components of the aircraft are fabricated. The major new materials used in these aircraft are titanium and composites.

The higher performance requirements of modern aircraft could only be attained by using these newer metals, alloys, and materials. In addition, some of the structural components of these aircraft have become more complex, and closer tolerances have been required. These technological changes in the design of the aircraft in turn have necessitated the development of new capital equipment and manufacturing technology. For example, the traditional method of machining an item was to remove material in the form of chips by using a cutting tool on a metal work piece. This operation was usually performed manually by a skilled craftsman operating one of a number of different types of machine tools. However, the more complex parts of the newer aircraft require three dimensional machinery with closer tolerances than can be attained with a manually operated tool. Consequently, the numerically controlled (NC) machine tool was introduced in 1956.

The early NC machines controlled only one tool; later versions, known as machining centers, had several different types of tools built into one machine. These machines automatically selected a tool, performed the necessary cutting operations, and then replaced the tool. The newest automatic tools are still more sophisticated, being directly controlled by small computers rather than by punched tape.

In terms of the manufacturing processes used by the aircraft industry, forming was not originally as important as machining among the aerospace industry's manufacturing techniques. Currently, the process of producing parts by pressing and forging is receiving greater attention. These forming processes save on both materials and machining time and produce parts which are near-net shape, i.e., very close in form to the required final product.

The greater interest in producing near-net shape parts was stimulated by the high and rising costs of the newer metals. Using the traditional methods of producing aircraft parts, ten pounds of metal inputs were often required to produce a finished part weighing one pound. Newer methods have reduced this ratio to 2:1. The industry has also developed and improved other methods for cutting and joining the newer high strength materials.

Finally, these industrial process innovations have had an impact on the labor force employed by the aerospace industry. First, the greater use of numerically controlled machines required the industry to hire more people to program these machines and substituted capital for production workers. Second, the industry is now required to produce more paper documentation along with the actual physical output. This has also required an increase in the number of employees who process these data. Both factors may help to explain why the composition of the industry's work force has changed, with a steady decline in the percentage of the industry's employees who are classified as production workers.

The dichotomy of product complexity and process innovation permits us to examine the effects that these technological changes have had on the costs of producing a particular aircraft. The particular question examined was: How would the production costs of a particular aircraft have changed if the technology utilized to manufacture a successor plane had been used to produce the original aircraft? A related question considered is: How do the costs of the successor aircraft compare to the costs of the earlier aircraft produced with the newer technology? These questions are related to the arguments presented above, where it was shown that cost movements which are attributable to technological change must be divided into two separate components--manufacturing technology and system complexity.

These questions are answered by using the F-4 as a case study. The actual costs of producing the F-4 are compared with estimated costs of manufacturing the F-4 with a newer production technology. These estimates are derived on the assumption that some of the F-15 technology would have been used to produce the F-4.

The results show that the use of the newer technology would have reduced the F-4 labor requirements by 26 percent but that overall costs would have decreased by only 12½ percent. This lesser decline in overall costs would be attributable to the substitution of other factors for labor. Nevertheless, the results lend credence to the hypothesis that, over time, new technological processes reduce the costs of manufacturing a particular weapon system.

Although incomplete, the data are sufficiently suggestive to support the hypothesis that the F-15 costs more than the F-4 would have cost if it had been produced with F-15 technology. It is estimated that an F-4 built with the newer technology would have utilized 26 percent fewer labor hours than were actually used to produce the F-15. This finding shows that improved performance accounts for increased costs. Although our study has focused on airframes, a less intensive analysis of radar systems (Appendix D) yielded similar results.

The implications of these findings for the existing cost estimating methodology include:

- These technological changes help to explain some of the biases which were observed in the cost estimates obtained from a preferred airframe CER (Chapter II).
- The overestimates of the number of manhours required for tooling can be explained by the substitution of capital for labor in this activity.
- Similarly, some of the underestimates in materials costs might result from the use of more expensive materials and the use of unitized components which entail more scrappage.
- *In the presence of technological change, the preferred airframe CER may no longer be valid.* For example, the CER for aircraft indicates that costs are positively related to the weight and maximum speed of the aircraft. However, the weight of modern aircraft is reduced only because more expensive materials have been substituted for the older, cheaper but heavier materials. Thus, with everything else held constant, weight and cost are negatively related--not positively as is implied by the CER.
- This finding leads to a more general conclusion. *A CER based on specific characteristics of older weapon systems may be used only if the characteristics of new systems do not require new production technologies,* i.e., if the relationship between system characteristics and the production function remains unchanged and stable.

Our summary recommendations involving modifications to the existing cost estimating methodology include:

- If the qualities or characteristics of newer systems require a new production technology, this factor must be incorporated into CERs.
- The characteristics that are included in a CER must in fact be the factors that drive costs.

- Thus, the complexity of the system or the requirement that a titanium-based technology must be used might be factors that drive costs.
- It might be possible to modify existing CERs by including an index of complexity, even though some previous studies have failed to find such a variable significant. While holding other system characteristics constant, such an index would shift a CER upward or downward, depending on the complexity of the product.
- An index of complexity would refer to both the system characteristics and the manufacturing technology required to produce the system. (Such an index might be constructed using the Delphi approach.)
- An additional variable that might be included in existing airframe CERs is the percentage of newer materials that are embodied in the airframe.
- Existing airframe CERs focus on manhours and materials costs. Given the recent substitution of company owned capital equipment for labor, some extra attention should be focused on analyzing the capital charges in the overhead rate.

Chapter I

INTRODUCTION

Previous economic analyses of the defense industries have developed several types of functional relationships between the cumulative output of a weapon system and its unit price or cost. These functions assume that other factors, such as the yearly rate of production of the particular item and the rate of technological change within that particular sector of the defense industry, would not affect this relationship. Nevertheless, even after adjusting for inflation, defense cost analysts have observed that the prices paid for many defense systems have exceeded the estimates which were derived from these cost relationships. It has become necessary to investigate the issue.

Structural changes have occurred in the defense industries; these changes may have changed the competitive practices, the nature of the product or the processes of production. Any of these changes may be affecting the cost relationships derived from earlier experiences in the industry, and the currently used estimating techniques may no longer be applicable. This paper, therefore, will investigate whether there have been major structural changes in particular segments of the defense industry and analyze the effects that any such changes have had on the appropriateness of the techniques used to estimate the costs of weapon systems.

The report is divided into several chapters. This chapter discusses the issue and sets a framework for the analysis. It defines both the types of structural change which will be analyzed and the sectors of the defense industries which will be considered. There is also a discussion of various functional relationships which are used to estimate the costs of weapon systems. Finally, an outline of the remainder of the study is presented.

A. SCOPE OF THE STUDY

1. Defense Industries

This study analyzes the structural changes that have occurred in the defense industries and the impacts that these changes have had upon techniques used to estimate weapon system costs; it is thus necessary to first define the limits of the defense industry.

The Commerce Department has classified 94 manufacturing industries as defense-oriented.[1] This definition includes both direct purchases and indirect expenditures on products that are eventually necessary for the production of defense goods, and is obviously too broad for the scope of this study. A RAND study selected 13 sectors of the economy as being essential to combat capability.[2] These sectors, listed in Table 1, produce "end-products most important to direct and indirect US military efforts...."[3] and are most representative of what might be considered US defense industries. Within the framework of this study it would have been impossible to undertake a complete analysis of the structural changes which have

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[1]U.S. Department of Commerce, Bureau of Census, *Shipments of Defense Oriented Industries*, MA-175(77)-1, 1977.

[2]Michael D. Miller, *Measuring Industrial Adequacy for a Surge in Military Demand: An Input-Output Approach*, The RAND Corporation, Santa Monica, CA, September 1978, R-2281-AF, p. 10.

[3]*Ibid.*

Table 1. THIRTEEN CRITICAL DEFENSE SECTORS

	Sector	Classification BEA	SIC	1977 DoD Sales ($ millions)[a]
1.	Complete Guided Missiles	13.01	3761	4,372.7
2.	Non Small Arms Ammunition	13.02	3483	601.1
3.	Tanks & Tank Components	13.03	3795	969.1
4.	Sighting & Fire Control Equip.[b]	13.04	3662,3832	(6495.3)(170.2)
5.	Small Arms	13.05	3484	150.3
6.	Small Arms Ammunition	13.06	3482	119.3
7.	Misc. Ordnance & Accessories	13.07	3489	242
8.	Radio/TV Communication Equip.	56.04	3662	6,495.3
9.	Aircraft	60.01	3721	7,501.9
10.	Aircraft Engines & Parts	60.02	3724,3764[c]	(3578.2)(598.2)
11.	Aircraft Propellers & Parts	60.03	3728	1,688.2
12.	Misc. Aircraft Equipment	60.04	3769,3728[d]	(646.5)(1688.2)
13.	Shipbuilding & Repairing	61.01	3731	2,899.2

[a]The 1977 sales figures are based on tables in *Shipments of Defense Oriented Industries*, U.S. Department of Commerce, Bureau of the Census, MA-175(77)-1, 1977.

[b]Electronic sighting and fire-control equipment is classified under SIC 3662, optical under SIC 3832.

[c]SIC 3724 includes aircraft engines and parts, and SIC 3764 includes space propulsion units and parts (these were classified together for the 1967 input-output analysis).

[d]SIC 3769 includes miscellaneous space vehicle equipment, and SIC 3728 includes miscellaneous aircraft equipment (these were classified together for the 1967 input-output analysis).

Source: Michael D. Miller, *Measuring Industrial Adequacy for a Surge in Military Demand: An Input-Output Approach*, The RAND Corporation, Santa Monica, CA, September 1978, R-2281-AF, p. 10.

occurred in all 13 sectors; therefore our analysis is focused on one particular defense product, military aircraft.[1]

2. Structural Changes

The term "structural changes" has many connotations in the context of industry studies. It can refer to the number of sellers or buyers, or differences in the competitive, contractual or legal practices which prevail in the industry. It can also refer to the various types of technological progress. All the aforementioned concepts are usually examined in the industrial organization literature which analyzes the relationship between structure, conduct, and performance.

Our attention is primarily focused upon those structural changes which affect production relationships and are the result of technological progress occurring either in the form of quality improvement or alterations of manufacturing techniques. These are the factors which affect the production function and costs and thus might alter traditional cost estimating techniques.

3. Technological Changes in Aircraft

This study focuses on the identification of technological changes in the military aircraft industry which have affected the costs of production and not on the character of competition. It is our belief that the primary factors changing these production relationships involve new processes and increases in the complexity of the systems. To gain an understanding of the dynamic processes that are involved, the methods for manufacturing the fighter aircraft produced circa

[1]There is also a short analysis of the technological change associated with the fire control equipment used in these aircraft. This analysis is presented in Appendix D.

1960 will be compared with the techniques used to make the current first line fighter aircraft.

B. COST ESTIMATING METHODOLOGY

After the dynamic processes involving technological change have been analyzed, we shall determine how these technological developments might affect the cost estimating methodology. It is important, therefore, to briefly describe this methodology as it currently exists.

1. Learning Curve

Cost information about weapons systems is required at all levels of the decision making process, and a methodology has evolved to provide cost estimates before the final configuration of the system is even known. Two basic concepts have been developed to provide this information. The first is the learning curve

$$C = AX^b \,, \tag{1}$$

where C is unit cost (expressed in real terms or manhours or manhours per pound), X is cumulative output, and b is called the slope of the learning curve.[1] It is, in fact, the slope if equation (1) is converted into a double log equation, i.e.,

$$\log C = \log A + b \log X \,. \tag{2}$$

The coefficient b then indicates what the proportionate change in costs would be for a proportionate change (usually a doubling) of cumulative output. Usually b is negative, indicating that unit costs decline with increases in cumulative

[1] Alternative terms for the learning curve are progress curve or experience curve.

output. This phenomenon is usually attributed to the learning associated with performing a repetitive manufacturing task.[1] The intercept of equation (2) indicates the unit cost of the first unit of output.

2. Cost Estimating Relationship (CER)

Estimates of the slope of the learning curve can provide information about the way unit costs behave with increases in cumulative output.[2] However, it is still necessary to make an estimate about the costs of a standardized quantity of each system so that the location (intercept) of the curve can be computed. This estimate usually is obtained from cost estimating relationships (CERs). This technique will be thoroughly described in Chapter II, but a brief summary of the approach is warranted here.

Cost estimating relationships must be used because costs cannot be derived from a bottom-up costing of subsystems and components. The bottom-up approach requires information about the final configuration of the system and the factor inputs to be used in the production process; such information usually is not available at the time that initial decisions about procuring the system must be made.

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[1]The seminal work on the learning curve phenomenon was written by Harold Asher, *Cost-Quantity Relationships in the Airframe Industry*, The RAND Corporation, Santa Monica, CA, July 1, 1956, R-291. Other works on the subject include: Jack Hirschleifer, "The Firm's Cost Function: A Successful Reconstruction?" *Journal of Business*, XXXV, No. 1, July 1962, pp. 235-255; Armen Alchian, "Reliability of Progress Curves in Airframe Production," *Econometrica*, Vol. 31, No. 4, October 1963, pp. 679-693; Walter Oi, "The Neoclassical Foundations of Progress Functions," *Economic Journal*, Vol. LXXVll, No. 307, September 1967, pp. 579-594; and R.A. Lloyd, "'Experience Curve' Analysis," *Applied Economics*, Vol. 11, 1979, pp. 221-234.

[2]This assumes that the slope of the progress curve is invariant with respect to similar types of systems.

Given this difficulty, a different approach, based on CERs, has been developed. Costs for systems are projected from statistical relationships (the CERs) estimated from the parameters which describe important characteristics of the system. For airframes, two important characteristics have been identified: weight and speed. The importance of each parameter in explaining the cost of the system is derived from regressions of the known characteristics of earlier systems upon the known costs of the same systems.

This approach completely abstracts from the production function, factor inputs and prices, and technological change. Moreover, the relationship between these parametric estimating techniques and the production function is not known, nor is it clear whether the parametric relationships remain valid if there is technological change, either in the methods of production or in the nature, quality, or complexity of weapon systems.

C. OUTLINE OF STUDY

In the second chapter the forecasting accuracy of one set of cost estimating relationships is considered. This is followed by a theoretical discussion of the functional relationship between the various cost estimating techniques, production functions, and technological change. The results of that chapter set the framework for the empirical analysis that follows. Chapter IV presents the results of previous studies of technological change in other industries. The complexity of modern fighter aircraft is analyzed in Chapter V, while the production techniques used to produce these aircraft are considered in Chapter VI. The subsequent chapter is a case study which shows how process and product changes affect production costs. Chapter VIII presents implications of the results and some recommendations. Appendices A, B, and C present technical material related to the body of this study, and Appendix D presents a short analysis of the technological changes which have occurred in a portion of the avionics industry.

Chapter II

AN EVALUATION OF AN AIRFRAME CER

A. INTRODUCTION

In the previous chapter it was stated that ideally a system's costs should be estimated from the inputs required to produce that system. Unfortunately, some cost estimates are required before the configurations of a system have been established. In that case it is impossible to determine what inputs would be required to produce the system, and costs cannot be estimated in this manner.

In those cases where the values of the required inputs cannot be determined, an entirely different methodology for estimating costs has been developed. The costs of particular systems are determined from parametric estimating relationships. These equations relate the costs of specific systems to key physical or performance characteristics of the systems. The values associated with each of the parameters are estimated empirically by a regression of the known costs on the specified parameters of systems which already have been produced. The costs of future systems are forecast by inserting the predicted performance and physical characteristics into the estimated equation and solving for the costs.

Although these parametric estimating equations (also known as cost estimating relationships, CERs) have been utilized for two decades, there is no published systematic evaluation of their forecasting accuracy. This chapter will undertake such an analysis.

The first part of this chapter will review some of the existing CER literature. A forecasting evaluation methodology then will be developed and, using these procedures, the accuracy of a particular CER will be examined.

B. REVIEW OF EXISTING LITERATURE

1. Airframe CERs

A majority of the fundamental work on CERs for defense systems has been developed by members of The RAND Corporation staff.[1] A number of other parametric estimating relationships have been developed elsewhere.[2] All of the previous studies relate the costs of acquiring a *specified number* of units of a particular defense system to important physical or performance characteristics of those systems.[3]

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[1]These studies include, G.S. Levenson and S.M. Barro, *Cost Estimating Relationships for Aircraft Airframe,* The Rand Corporation, RM-4845-PR (abridged), April 1966; G.S. Levenson, *et.al, Cost Estimating Relationships for Aircraft Airframes,* The RAND Corporation, R-761-PR, December 1971; Joseph P. Large, Harry G. Campbell and David Cates, *Parametric Equations for Estimating Aircraft Airframe Costs,* The RAND Corporation, R-1693-1-PA&E, February 1976; and J.R. Nelson and F.S. Timson, *Relating Technology to Acquisition Costs,* The RAND Corporation, R-1288-PR, March 1974.

[2]These studies include, Planning Research Corporation, *Methods of Estimating Fixed-Wing Airframe Costs,* PRC R-547, Vol. I, February 1965, also Volumes I & II, R-547A, April 1967; J.V. Yance, *Airframe Cost Analysis: Navy Combat Aircraft,* Research Contribution No. 9 (Institute of Naval Studies, Center for Naval Analysis), June 1965; J.W. Noah, *et al., Estimating Aircraft Acquisition Costs by Parametric Methods,* J. Watson Noah Associates, Inc., FR-103-USN, September 1973; and R.A. Groemping and J.W. Noah, *Estimating Aircraft Acquisition Costs by Parametric Methods,* J. Watson Noah Associates, Inc., TR-10618-USN, May 1977.

[3]These CERs are similar to hedonic price indexes in which prices of particular commodities are related to characteristics of those products. The hedonic price indexes are used to distinguish price changes attributable to quality changes from pure price increases for an analysis of hedonic price indexes. See Zvi Griliches, ed., "Price Indexes and Quality Change," Harvard University Press, Cambridge, Mass., 1971.

The RAND studies have shown that the most important determinants of airframe costs are the airframe unit weight (W) and maximum speed, S. The RAND regression equation[1] which best explains cumulative total engineering hours for 100 units is:[2]

$$E_{100} = .023\ (W)^{.66}\ (S)^{.96}$$

$$R^2 = .90.$$

Similar equations were derived for tooling hours,[3] manufacturing hours (both non-recurring and recurring), manufacturing materials, and flight testing. In addition, the identical equations were estimated for other quantities of output, i.e., 25, 50 and 200 airframes. The non-RAND models explain the costs of a specified quantity of airframes with variants of the speed and weight variables, but other characteristics are frequently included in the equations.

2. CERs For Other Systems

Parametric estimating techniques have also been used to estimate the costs of other components of defense systems. The crucial characteristics that were included in the CERs

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[1]The equation is estimated in log-linear form, i.e., $\log E_{100} = \log A + b \log (W) + c \log S$.

[2]Large, Campbell and Cates, *op.cit.*, p. 20.

[3]Tooling hours were defined as "all effort expended in tool and production planning design, fabrication, assembly, installation, modification, maintenance, and rework of tools, and programming and preparation of tapes for numerically controlled machines," *idem.*, p. 23.

for jet engines were development time, thrust and Mach number.[1] For phased radars, cost was a function of the number of transmitting and receiving elements, power output, number of targets tracked, etc.[2] In some cases quantity procured or production rates are included in the estimating equations.

3. Technological Factors in CERs

Given the concern of this analysis with the effect of technological change upon weapon system cost, it is important to determine whether variables which measure changes either in the quality of the product or in the techniques of production have been incorporated into CERs. A number of attempts have been made to include some measure of quality change in the CERs. While the RAND airframe CERs do not explicitly include technological variables, one study[3] included time as a proxy variable to capture some of the effects produced by the required changes in the state of the art. The time variable was statistically significant in these airframe CERs.

The Noah CERs explicitly contain two variables which represent the effects that technology has on costs. The first variable is an index of technological advance as measured by the number of model changes that a particular aircraft experienced.[4] The second explanatory variable measures the

[1]See for example, F.A. Watts, *Aircraft Turbine Engine: Development and Procurement Cost,* The RAND Corporation, RM-4670-PR (abridged), November 1965; J.P. Large, *Estimating Aircraft Turbine Engine Costs,* The RAND Corporation, RM-6384/1-PR, September 1970.

[2]Gene H. Fisher, "Cost Considerations in Systems Analysis," American Elsevier Publishing Co., Inc, N.Y., 1971, p. 129.

[3]Large, Campbell, and Cates, *loc. cit.*

[4]This variable sometimes produced peculiar results. See J.P. Large and Capt. K.M.S. Gillespie, *A Critique of Aircraft Airframe Cost Models,* The RAND Corporation, R-2194-AF, September 1977.

complexity of the aircraft and is represented by a (0, 1) dummy variable.[1] An aircraft either is considered complex, in which case the value 1 is assigned to the dummy, or simple, in which case the dummy has the value 0. These assignments were determined judgmentally.

The PRC study also incorporates time into the CER, but this variable captures cost increases due to both technological changes and inflationary pressures.

Nelson and Timson developed an indirect method for incorporating effects of the required technological advance into aircraft engine CERs. They first represented the technological advance as a function of the date that an engine with a specified set of technical characteristics was expected to attain a specified level of performance. This is called the time of arrival (TOA). The difference between the predicted[2] and actual TOAs was then included in the engine CERs. Finally, Harman[3] attempted to relate acquisition cost overruns to *subjective* measures of the technological advances required to develop aircraft and missiles.

While there have been some attempts to include technological quality changes in some of the CERs, the currently preferred airframe equations do not include such variables. Moreover, none of the CERs takes into account changes in production techniques. The performance of the CERs might be affected by the exclusion of both types of variables.

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[1]Dummy variables of this type shift the intercepts of the CERs.

[2]The predicted time of arrival is a function of temperature, pressure, specific fuel consumption, and maximum thrust.

[3]Alvin J. Harman, *Acquisition Cost Experience and Predictability*, The RAND Corporation, P-4505, January 1971. Large, Campbell and Cates, *op. cit.* p. 44-45 also used a subjective difficulty index but rejected the approach.

4. Previous Critique of CERs

Large and Gillespie[1] compared some of the airframe CERs developed by different organizations and examined the variables which were included in the equations. A subset of these CERs was used to make cost predictions for nine military airframes. The study showed that all of the equations had some deficiencies, but that the newer equations performed better.

Unfortunately, the Large and Gillespie study contains an inconsistency. Each of the alternative CERs was used to predict the costs of the same identical nine airframes. However, in some cases forecasts were made for aircraft which were in the data base from which a particular CER was derived. In other cases, some of the aircraft were not included in the data base from which the CER was estimated, and the cost estimates for the aircraft which were excluded were true post-sample forecasts. It is inappropriate to compare one set of cost "forecasts" which were partially derived from observations contained within the sample with a different set which were obtained, partially or entirely, from data outside the sample. Given this inconsistency, it is not entirely possible to determine how well CERs predicted the cost of systems which were completely outside the sample.

C. EVALUATION OF AN AIRFRAME CER

In the remainder of this chapter a methodology for evaluating the forecasts of CERs is developed, and this procedure is applied to an evaluation of the cost estimates obtained from a preferred RAND airframe CER. The purpose of this exercise is not to critique the particular RAND equation, but rather to determine whether a CER which contains no explicit technological change variables might exhibit any

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[1]Large and Gillespie, *loc.cit.*

forecasting biases. This evaluation might also shed light on the effect that technological changes have had on the CERs. The RAND data base was accessible to the staff of the Office of the Assistant Secretary of Defense, (PA&E).[1]

We shall first describe the equation that was used. This will be followed by an explanation of the evaluation procedure. The results and interpretation will comprise the last section.

1. RAND Airframe CER

It has been shown that the preferred RAND CER was of the form

$$L_x = AW^{\alpha}S^{\beta} ,$$

where L_x is the cumulative labor hours of a specified type utilized to produce the first x units of an airframe, W is the weight,[2] and S is the maximum speed of the aircraft. These figures are contained in the RAND data base and are available for most post-war aircraft. The latest published RAND airframe CER is based on data for 25 military aircraft.[3] The equation is usually estimated in the log-linear form

$$\log L_x = \log A + \alpha \log W + \beta \log S .$$

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[1]Lt. Col. Douglas Fisher of that office developed many of the data which are contained in the evaluation. We wish to thank him for his efforts. Any errors in interpretation, etc., are solely the responsibility of the authors of this report.

[2]Airframe unit weight is empty weight minus a large number of items including (1) wheels, brakes, tires and tubes, (2) engines, (3) fuel cells, (4) starters, (5) propellers, (6) instruments, (7) avionics, etc. The remaining items are listed in Large, Campbell, and Cates; *op.cit.*, p. 19.

[3]Large, Campbell and Cates, *op.cit.*, p. 5. The first flight dates were from 1953-1970. A subsequent and still unpublished RAND study also excluded the A-7, T-39, and F-3, but added the S-3A, F-15 and A-10.

The CER is estimated for several types of labor manhours--engineering, tooling and manufacturing. It is also used to estimate the manufacturing material utilized in the airframe. Conceptually, a CER may be estimated for different levels of cumulative output. The RAND study constructed CERs for the first 25, 50, 100 and 200 units.

2. Evaluation Procedure

The analysis will evaluate the accuracy and stability of the aforementioned CER. Specifically, the evaluation will determine how well the CER predicted outside the sample, and whether the α and β coefficients in the estimated equation remain stable when additional data points are included in the sample. Although CERs could have been estimated for different levels of cumulative output, our analysis was confined to evaluating the CER relating to the first 100 airframes.

The evaluation procedure was to divide the available data into two groups. The first group constituted the sample from which the CER was statistically estimated. The second group contained the observations which the estimated CER was to predict. In our analysis, data on twenty-five aircraft were initially available;[1] twenty were used to estimate the CER, which was then used to predict the various manhours and materials required to construct the excluded five aircraft, which were the last developed.

The predictions for the five aircraft were obtained by inserting the known values of speed and weight into the estimated CERs. These predictions were then compared with the actual (and known) observations relating to these airframes; the differences between these figures were the forecasting

[1]This is based on the data files which exclude the A-7, T-39, and F-3. These files include data on both large and small military aircraft with first flights since 1952.

errors (for the five airframes) attributable to the equation.[1] The percentage error for each of the five airframes was computed.

The procedure was repeated iteratively by adding one aircraft to the sample and predicting one less observation until there were twenty-four data points in the sample and one observation to be predicted. This iterative procedure determined whether the forecasting results were sensitive to the sample size. The five aircraft which were originally excluded from the sample and for which costs were predicted were the A-10, C-5A, F-14, F-15, and S-3A; they have been labelled aircraft 1 through 5.[2]

In addition to measuring the forecasting accuracy of the CERs, the analysis examined the stability of the coefficients of the equation as additional observations were added. Thus for the CER for engineering hours, there would be five sets of estimates for the coefficients associated with the weight and speed variables, e.g., for 21...25 data points.

3. Results

a. Forecast Errors

The percentage forecast errors which were made by the CERs for engineering hours, tooling hours, manufacturing

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[1]This procedure for measuring forecasting errors is known as *ex post* analysis in the macroeconomic forecasting literature. It is designed to evaluate the accuracy of a forecasting technique when the independent variables contained in the equation are known. It is a true measure of forecasting accuracy of the *technique*. However, in actual practice a decision maker would use the technique by inserting *estimated* values of the independent variables. These *ex ante* forecast errors would then result from both the mis-estimates of the independent variables and the technique's inaccuracy.

[2]The numerical orderings do not necessarily correspond to the alphabetical listing.

hours and manufacturing material are presented in Tables 2 through 5. For all categories of cost, the errors for a particular analysis are relatively insensitive to the number of observations used to estimate the CER from which the specific costs are predicted. For example, the percentage error for engineering hours for aircraft 3 only varies between -74.7 percent and -75.0 percent when the number of sample points is increased from 20 to 22. For aircraft 4, the range (4 observations) is -29.5 percent to -32.7 percent, while aircraft 5 shows a somewhat larger range (5 observations): -39.2 percent to -48.5 percent. Similar findings hold for the other elements of cost, with underestimates always remaining underestimates, etc.

However, differences occur between the various categories of costs. Engineering costs are uniformly underestimated and the errors are substantial. Except for aircraft 1, tooling costs are generally overestimated. The manufacturing hours' forecasts all show errors which are less than 20 percent, and there is no observed bias. On the other hand, the manufacturing material costs' errors also display a mixture of over and underestimates, but the discrepancies are substantial in several cases.

These findings indicate that there are systematic biases in the engineering and tooling hours' estimates. In addition, the manufacturing materials' estimates display sizable errors. These findings suggest that there may have been systematic structural changes which affected the process by which airframes were produced. These changes may have resulted from the substitution of one type of labor for another, the introduction of labor saving capital, the use of new materials or the effect of technological change in general. In any event, one or more of these factors has affected the accuracy of existing CERs.[1]

b. Coefficient Stability

The coefficients for the four CERs estimated from different sample sizes are presented in Table 6. The results indicate that the coefficients of the manufacturing hours CER do not vary much with changes in the sample size. However, for the other CERs, one or the other of the two coefficients shows considerable variation when the sample size is incremented from 20 to 25. For example, the speed coefficient (β) of the engineering hour equation has a 20 percent range. Although no formal statistical test was performed, it appears that at least some of the CERs do not have stable coefficients.[2] Given this instability, it is likely that the given CER might not be appropriate for forecasting the costs of future airframes.

4. SUMMARY

The results relating to both the ex post forecast errors and the stability of the coefficients of the CERs suggest that fundamental changes which affect these CERs have been taking place. It is important to investigate and understand what these changes have been. Therefore, in the next chapter we shall analyze the relationship between CERs, production

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[1]In view of the production technology changes which have occurred, the finding with respect to manufacturing hours is surprising. However, increased fabrication costs may have been offset by a decline in assembly line hours.

[2]Although the results are not presented here, some of the older excluded aircraft (such as the A-7, T-39, F-3, F-101, F-89, D-47, F86A and F84A) were added to the sample. The size of the coefficients varied even more. However, the range of the coefficients associated with incrementing the sample with the *last five* observations remained the same as reported.

functions and learning curves. An understanding of this relationship will provide a conceptual framework for describing the dynamic changes which have affected the accuracy of the CERs.

Table 2. EX POST PERCENTAGE ERRORS OF CER IN FORECASTING ENGINEERING HOURS FOR 5 AIRFRAMES, 100 UNITS (+ OVERESTIMATE, - UNDERESTIMATE)

Specific Aircraft (Number)	NUMBER OF OBSERVATIONS IN SAMPLE				
	20	21	22	23	24
1	-44.9	--	--	--	--
2	-23.3	-20.0	--	--	--
3	-74.7	-74.7	-75.0	--	--
4	-32.7	-31.7	-29.5	-32.7	--
5	-47.7	-48.5	-49.2	-39.2	-39.9

Table 3. EX POST PERCENTAGE ERRORS OF CER IN FORECASTING TOOLING HOURS FOR 5 AIRFRAMES, 100 UNITS (+ OVER-ESTIMATE, - UNDERESTIMATE)

Specific Aircraft (Number)	NUMBER OF OBSERVATIONS				
	20	21	22	23	24
1	-6.5	--	--	--	--
2	+26.3	+26.9	--	--	--
3	+16.9	+16.9	+18.5	--	--
4	+19.7	+19.9	+15.8	+16.5	--
5	+88.5	+88.2	+90.9	+86.7	+87.5

Table 4. EX POST PERCENTAGE ERRORS OF CER IN FORECASTING MANUFACTURING HOURS FOR 5 AIRFRAMES, 100 UNITS (+ OVERESTIMATE, - UNDERESTIMATE)

Specific Aircraft (Number)	NUMBER OF OBSERVATIONS				
	20	21	22	23	24
1	-5.5	--	--	--	--
2	+5.6	+6.0	--	--	--
3	-15.0	-15.0	-14.7	--	--
4	-7.8	-7.7	-8.4	-8.9	--
5	+15.3	+15.1	+15.5	+17.9	+17.6

Table 5. EX POST PERCENTAGE ERRORS OF CER IN FORECASTING MANUFACTURING MATERIAL (CONSTANT DOLLARS) FOR 5 AIRFRAMES, 100 UNITS (+ OVERESTIMATES, - UNDERESTIMATES)

Specific Aircraft (Number)	NUMBER OF OBSERVATIONS				
	20	21	22	23	24
1	-48.5	--	--	--	--
2	+12.8	+18.2	--	--	--
3	-52.9	-53.0	-52.6	--	--
4	+6.1	+7.8	+5.3	+2.6	--
5	-31.4	-32.7	-32.0	-25.1	-25.0

Table 6. VARIATION OF COEFFICIENTS OF WEIGHT (α) AND SPEED (β) IN VARIOUS CERs WITH CHANGING SIZE OF THE SAMPLE FROM 20 TO 25

	COST ESTIMATING RELATIONSHIPS							
	Engineering		Tooling		Manufacturing Hour		Manufacturing Material	
Sample Size	α	β	α	β	α	β	α	β
20	.636	1.03	.558	.386	.744	.332	.833	.928
21	.702	1.05	.566	.388	.750	.333	.907	.948
22	.710	1.09	.558	.344	.748	.322	.901	.917
23	.656	.886	.564	.369	.742	.299	.872	.808
24	.659	.939	.563	.348	.742	.312	.872	.805
25	.637	.875	.590	.427	.749	.332	.859	.769

Chapter III

THE THEORETICAL RELATIONSHIPS BETWEEN LEARNING CURVES, COST ESTIMATING RELATIONSHIPS AND PRODUCTION FUNCTIONS

The previous chapters explained the meaning of learning curves and cost estimating relationships (CERs). This chapter will develop the interrelationship between the learning curve and a CER and then relate both concepts to certain other concepts of economic theory, namely production functions and technological change. The purpose of this analysis is to show how learning curves and CERs are fundamentally related to basic economic concepts. The conditions under which CERs might yield meaningful cost predictions will be developed and the types of technological changes which cause CERs to yield less meaningful estimates will be examined.

A. INTRODUCTION

1. Learning Curves and CERs

It has been shown that the commonly used learning curve is of the form

$$C_x = AX^a \qquad (1)$$

where C_x is the unit incremental cost of the x^{th} unit, x is the cumulative output and $a<0$ is a parameter representing the degree of learning. Similarly, a CER is of the form

$$TC_x = \alpha Q_1^{\beta} Q_2^{\gamma} \qquad (2)$$

where TC_x represents the total cost of producing x units, Q_1 and Q_2 are particular qualities and/or characteristics which describe the system and affect the costs, and α, β and γ are parameters. It should be noted that for any specified outputs, the three parameters need not be equal to the same parameters for any other specified level of output. Since different parameters would arise for different outputs, the CERs are *implicitly* incorporating some of the learning phenomena into the parameter estimates. The learning curve may incorporate some of the quality characteristics if the rate of learning varies with the complexity of a system.

Finally, it should be noted that neither the learning curve nor the CERs explicitly incorporate any information about the factors of production or technological change, or about the interaction between production techniques, quality changes and technological changes. This is despite the fact that the aforementioned economic processes determine costs and learning. An analysis which explicitly relates learning curves and CERs to production processes requires the use of generalized production functions.

2. Production Function

The economist's production function is an analytic concept which relates input flows of capital (K), labor (L) and materials (M) to the maximum attainable output flow (Q) of any product:

$$Q = f(K,L,M,) . \qquad (3)$$

For this study we shall use a fictional F-x aircraft as the output. The dimensions of inputs and outputs in (3) are rates of flow per unit time period. That is, to attain an output flow of (say) 5 F-xs *per month* requires (say) 160 hours of capital services per month, 32,000 labor hours per month, and 100,000 tons of materials per month. Other factor combinations will also produce at this output rate, since (3) is very general and permits substitution among inputs.

The production function (3) is so general that economists have often specified particular forms of the production relationship in their analyses. We shall be using the Cobb-Douglas version of the relationship:

$$Q = BK^{c}L^{b}M^{k} . \qquad (4)$$

This form has commonly been used by economists and its characteristics are well known.[1]

If a time period equal to the average time necessary to produce an F-x (say, 1 week) is chosen, it is possible to define for Q = 1; that is, for a rate of one F-x per week

$$Q = 1 = BK^{c}L^{b}M^{k} . \qquad (5)$$

Then, K, L, and M are the minimum amounts of inputs necessary to produce on F-x--the unit input amounts--and we will so interpret them in the analyses to follow.

3. Technical Change

a. Disembodied Change and Learning

The production function (5) does not incorporate any characteristics associated with technical change. It assumes that the production relationships among inputs and outputs do not vary over time and that the quality of the product

[1] For a discussion of the characteristics of the Cobb-Douglas function, see James M. Henderson and Richard E. Quandt, "Microeconomic Theory," McGraw Hill, N.Y., 1971, pp. 80ff.

does not change. Both relationships do, in fact, change over time, and our analysis must take them into account.

Economists have stressed that there are two kinds of technical change which affect the production relationship. The first, termed *disembodied* technical change, arises when certain efficiencies are attained with any changes in the *types* of capital, labor, or materials used. It is termed disembodied technical change because it is not associated with new technological developments *embodied* in capital, labor, or materials.

Disembodied technical change may arise from capital, labor, or materials. For example, over time the company's management and engineers learn to use the plant and equipment more efficiently by better routing of product, scheduling of processes, maintenance, etc. This is a manner of enhancing the capital services rendered by a fixed plant and equipment, or, for each F-x, of reducing the amount of capital services needed. Even more important is the greater efficiency that the labor force acquires through experience. Laborers learn advanced skills and management learns how to use the labor force more efficiently. Finally, materials usage may be expected to improve, with lessening of waste as cutting of aluminum sheets is done more efficiently, fewer mistakes are made, better recycling of scrap is achieved, etc.

Since this type of technological change may be viewed as enhancing the quantity of factors which are used to produce the F-x, it does not require that one factor be substituted for another. Hence, disembodied technological progress may be viewed as neutral in its impact upon the production function (5).

While in theory it is possible to decompose disembodied technical changes into their effects on the three factors, in practice it is not possible to do so. We therefore combine all these changes into a single rate of technical progress, r, and incorporate it into the production function (5) to obtain:

$$1 = Be^{rt}K^{c}L^{b}M^{k} . \qquad (6)$$

As each week passes the learning term e^{rt} rises, which implies that the input complex $K^{c}L^{b}M^{k}$ falls:

$$K^{c}L^{b}M^{k} = B^{-1}e^{-rt} . \qquad (7)$$

Since it has been assumed that it takes one week[1] to produce each F-x, t measures both the number of weeks that have passed in the production process and the *cumulative* output, X, of F-xs. We may therefore rewrite (6) as

$$1 = Be^{rX}K^{c}L^{b}M^{k} , \qquad (8)$$

and (7) as

$$K^{c}L^{b}M^{k} = B^{-1}e^{-rX} . \qquad (9)$$

Finally, it should be noted that this disembodied technical change will be associated with "learning."

b. Embodied Technological Change

A second type of technological change consists of a discontinuous break in the methods of production requiring a

[1]It should be noted that the use of cumulative output as a surrogate for technical progress or "learning" is in contrast to Arrow's explicit rejection of this concept. Arrow uses cumulative gross investment, but his object is to explain macroeconomic technological changes and all progress is endogenized. See Kenneth J. Arrow, "The Economic Implications of Learning by Doing," *Review of Economic Studies*, Vol. 29, No. 80, April 1962, pp. 155-173.

move to a different function. In its simplest form the change from an old to a new function is simply a proportional reduction in all inputs required to produce a standardized output:

$$1 = \theta B e^{rX} K^{c} L^{b} M^{k} , \quad \theta > 1 . \tag{10}$$

We shall call this type of change *composition neutral* because it does not affect the relative proportions in which K, L, and M are used.[1]

It is expected that embodied technological change will affect the factors in different ways and that it will not be composition neutral. Thus, a robotized assembly machine would be expected to alter the substitution relationships among inputs, e.g., less labor than was previously used would be required on the assembly line. This type of technological change is not associated with learning because it is accompanied by changes in the types of capital, labor, or material used in the production process.[2]

c. Summary

There are two types of technical change, disembodied and embodied. Disembodied technical change does not affect the substitution relationship among the factor inputs, is factor neutral, and is associated with learning. Embodied technical change usually will affect the relationships among the inputs and consequently may not be factor neutral.

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[1] As an example, a new method of installing the engines reduces capital, labor, and materials' needs proportionally, although it requires the installation of some replacement capital. Or, faster methods of moving materials through the production process might effect similar savings, although newly developed capital goods must be employed in place of old.

[2] The mathematical representation of this type of technological change is presented in Appendix A.

B. COST FUNCTIONS AND LEARNING CURVES

1. Disembodied Technical Change

It is possible to derive cost functions from any production function. The cost functions obtained from the Cobb-Douglas function with disembodied technical change are derived in Appendix B. The results indicate that the minimum cost of the x^{th} unit will be of the form

$$C_x = Ue^{-rX} . \qquad (11)$$

As x increases, C_x will follow the exponential function (11) rather than the usual logarithmic formulation of the learning curve

$$C_x = AX^a . \qquad (12)$$

This result implies that if the technology can be represented by a Cobb-Douglas production function, then the *learning curve* (12) *customarily used is only an approximation of the true learning curve* (11). Nevertheless we shall use (12) and assume that it is a good approximation of (11).[1]

Appendix B also demonstrates that the conventional learning curve (1) may be related to the production function with disembodied technical change:

$$C_x = \frac{A}{a} [BK^cL^bM^k)^{-1} - 1]^a , \qquad (13)$$

where

$$K^cL^bM^k = B^{-1}e^{-rX} . \qquad (14)$$

[1]Both curves are convex functions (if $r \geq 0$ and $a \leq 0$), but the functional relationship between r and a is complicated.

Let us interpret these relations. The learning curve is a reflection of generalized or "disembodied" technological progress that springs from using labor and materials more efficiently with experience. The factor proportions [K/L, M/L] will be determined by factor prices and minimum-cost analysis (see Appendix B). The factor requirements for each successive F-x will conform to (13), falling as x rises. These reduced $K^c L^b M^k$ terms in turn will reduce costs in conformance with the learning curve.

2. Embodied Technical Change

It is possible to derive similar relationships between learning curves and production functions when embodied technical change is present. The results of Appendix B indicate that embodied technological change lowers the position of the learning curve. Moreover, if the embodied change is composition neutral, and if the learning rate is unchanged, then the new curve will be parallel to the old on a double log grid.

If the technology provides a lesser opportunity for "learning," the old and new learning curves will not be parallel. In addition, if the technological change is not factor neutral, the implied learning curves again will not be parallel.

3. Summary

Our analysis has shown that the learning curve used in cost analysis is related to the cost functions obtained for cost minimizing procedures applied to production functions. The learning curves can also be directly related to production functions which include either disembodied or embodied technological change.

C. PRODUCT QUALITIES, CERs, PRODUCTION FUNCTIONS, AND LEARNING CURVES

Our analysis has established that the production function and learning curves are related. The remaining task is to establish the functional relationship between CERs, the production function, and the learning curve. In order to establish this relationship, it is first necessary to analyze the effect that changing product qualities has upon the production function. This procedure is required because CERs relate costs to product qualities, but the production functions analyzed above have not considered how these product characteristics affect factor inputs and costs.

1. Product Qualities, Production Function, and Learning Curves

Aircraft CERs have previously assumed that two relevant characteristics, weight and speed, best explain the cost of developing and manufacturing aircraft. We shall now determine the conditions under which it is possible to derive the learning and cost curves for the F-x from these product qualities. We shall assume that the F-x has speed and weight characteristics which are different from those associated with previous aircraft. However, we shall also assume that the F-x can be produced with essentially the same disembodied and embodied technology.

This assumption implies that the new qualities will have no impact upon the minimum-cost factor proportions. Consequently, the Cobb-Douglas production function with technical change may now be written in the form

$$1 = B(\delta Q_1+\delta_2 Q_2)\ e^{rx} K^c L^b M^k \ , \tag{15}$$

where Q_1 and Q_2 are measures of the qualities of the system, in this case speed and weight.

The learning curve can be derived as previously, yielding

$$C_x = \frac{A}{r^a}\left[(B(\delta_1 Q_1+\delta_2 Q_2)\ K^c L^b M^k)^{-1}\right]^a, \tag{16}$$

$$K^c L^b M^k = B^{-(\delta_1 Q_1+\delta_2 Q_2)} e^{-rX} . \tag{17}$$

The question that must now be addressed is: How does the learning curve of the F-x differ from that of other aircraft when the weight and speed of the F-x are taken into account. It can be demonstrated (see Appendix C) that for any specified output, the two learning curves will differ only by a multiplicative factor, Ω. Thus the learning curve for the F-x would be parallel to the learning curve for older aircraft, and the total costs for any specified quantity would also differ by this multiplicative factor.

However, this conclusion holds only with three crucial assumptions:

- Product qualities change in a factor neutral manner.
- Technology remains constant.
- The rate of learning (disembodied technological change) does not change.

2. CERs and Quality Changes

The CER is of the form

$$C_x = DQ_1^m Q_2^n . \tag{18}$$

Let us now compare the predicted costs of the F-x obtained from its characteristics Q_{1x}, Q_{2x}, with the costs of other aircraft obtained from their characteristics. For a specified quantity of the F-x,

$$C_{F-x} = DQ_{1x}^m\ Q_{2x}^n . \tag{19a}$$

For other aircraft with the same output,

$$C_0 = DQ_{10}^{m}Q_{20}^{n} \; . \tag{19b}$$

The ratio of the two costs (19a, 19b) for the same output is a multiplicative factor:

$$\frac{C_{F-x}}{C_o} = \left(\frac{Q_{1x}^{m}\; Q_{2x}^{n}}{Q_{10}^{m}\; Q_{20}^{n}}\right) = \psi \; . \tag{20}$$

3. Comparison of CERs and Production Learning Curves

The conclusions of the previous two sections indicate that quality changes shift both the learning curve and CERs by multiplicative factors. The first shifts by the factor Ω; the latter by the factor ψ.

However, this finding does not indicate that the two approaches will yield identical results. It must be remembered that three assumptions were required to demonstrate that the learning curve shift was multiplicative. Moreover, the two multiplicative factors, Ω and ψ, need not be identical.

Thus, we cannot conclude that the cost estimates obtained directly from CERs and those derived from production functions incorporating qualities must be identical. Moreover, when the three assumptions associated with the learning curve are relaxed, there is even less likelihood that the two estimates are similar.

D. SUMMARY

This chapter has shown that there is a direct relationship between the production function and learning curves. The analysis showed that disembodied technical change is associated with learning. The production function approach was expanded to show how product quality changes would affect the cost of production. The theoretical cost predictions obtained from CERs were compared with the estimates that the production function would have generated. It was shown that the two approaches would yield similar results only if a large number of assumptions were made.

Chapter IV

PREVIOUS INDUSTRY STUDIES OF TECHNOLOGICAL CHANGE

Chapter III (and the associated Appendices) demonstrated that the production costs of a given system may be affected by two types of changes. First, there may be technological changes which affect the methods of production, and these changes usually lower the costs of producing a given system. Second, there may be changes in the quality or characteristics of the system. These product innovations may either increase or decrease costs, depending on the direction of change. Increasing complexity and improving the quality of the product would generally increase costs, and vice versa.

It is possible to illustrate the two concepts theoretically. Figure 1 shows how the time trend of costs of an increasingly complex system can be divided into the two effects, increased complexity and lowered production costs.

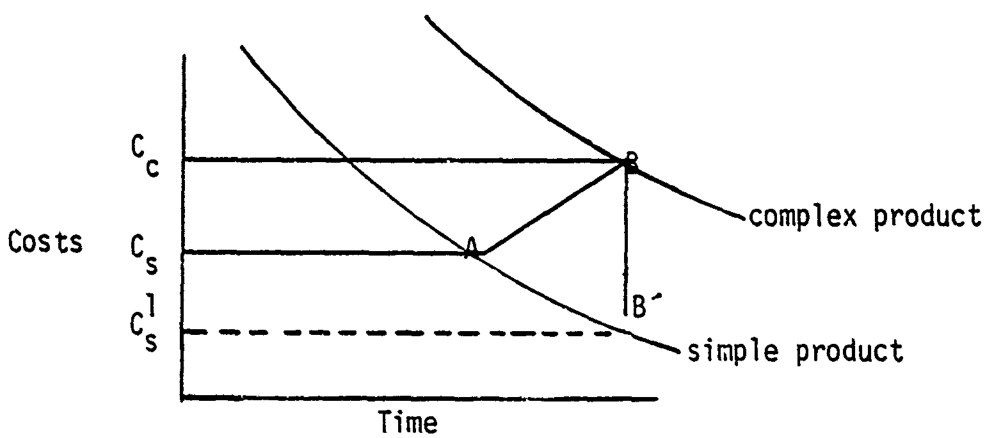

Figure 1. COSTS OF PRODUCING SIMPLE AND COMPLEX PRODUCTS WITH TECHNOLOGICAL CHANGE

Over time, the unit costs of producing a standardized quantity of the system rise from C_s to C_c. This increase, however, is the result of two offsetting movements. If the quality of the product had remained unchanged, embodied and disembodied technological change would have reduced the costs to C_s^1. However, the newer system became more complex, as illustrated by a higher cost relationship. The effect of this increased complexity is measured by the distance B-B' or $C_c - C_s^1$.[1]

While it is possible to illustrate these separate effects, it is empirically difficult to divide the observed results into the two distinct components.[2] Generally, previous economic analyses of product and process innovations have not separated the two effects. It would be instructive to survey the existing industry literature on technological change to examine both the methodology and findings.

A. GENERAL STUDIES

There is a considerable literature on the relationship between research and development, innovation, and the diffusion of new procedures and economic variables such as market structure. These studies have been summarized by Kamien and

[1]If the system had become simpler, the new curve would have lain below the cost relationship for the simple product. In that case the two effects would have reinforced each other and the *actual* costs would have declined over time.

[2]Blaug had a similar observation when he indicated it was possible to distinguish new ways of making old products from old ways of making new products. An analysis involving new products *and* new techniques is more difficult. See M. Blaug, "A Survey of the Theory of Process - Innovation," *Economica*, February 1963, pp. 13-32.

Schwartz,[1] Gold,[2] Kennedy and Thirlwall,[3] Gold, Rosegger, and Boylan,[4] and Scherer.[5] While it is not necessary to review this literature, several points should be noted.

First, little effort is made to distinguish between process and product innovations. The reasoning is that the improved product originating in one industry becomes the improved process of another industry.[6] This approach is appropriate in considering the economy-wide interrelationships between innovation and economic variables. It is not appropriate in analyzing technological change in *one* industry.

Moreover, it is possible that the process and product innovations of one industry are interrelated. For example, a new and improved aircraft, when produced, would be considered a product innovation. However, some performance characteristics (such as higher speed) of that aircraft might require that the aircraft be constructed from newer materials such as titanium. The techniques for producing an aircraft made from titanium are different from the processes used to manufacture an aircraft primarily utilizing aluminum. Thus, new processes for machining and fabricating titanium parts must be incorporated into the aircraft manufacturing process.

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[1]Morton I. Kamien and Nancy L. Schwartz, "Market Structure and Innovation," *Journal of Economic Literature,* XIII, No. I, March 1975, pp. 1-37.

[2]Bela Gold, ed., "Research, Technological Change and Economic Analyses," Lexington, Mass, Lexington Books, 1976.

[3]C. Kennedy and A.P. Thirlwall, "Technical Progress: A Survey," *Economic Journal,* Vol. 82, No. 325, March 1972, pp. 11-72.

[4]Bela Gold, Gerhard Rosegger, and Myles G. Boylan, Jr., *Evaluating Technological Innovations: Methods, Expectations and Findings,* Research Program in Industrial Economics, Case Western Reserve Univ., 1979.

[5]Frederic M. Scherer, "Industrial Market Structure and Economic Performance," Chicago, Rand McNally, 1980, pp. 407ff.

[6]Kamien and Schwartz: *op.cit.,* p. 2.

The process innovation is consequently directly connected to innovation.[1]

In examining these specific industry studies, we shall be interested in determining whether they shed light on the basic issues of concern:

- What is the relationship between product quality and the production function, especially if the new qualities require a new technology?
- What is the behavior of costs for fixed product qualities when there is technological progress, either of the embodied or disembodied variety?

B. STUDIES OF SPECIFIC INDUSTRIES

1. Light Bulb Production

Bright[2] described, for thirteen cases, the benefits and costs of introducing newer automated equipment and the implications of this automation for business management. The analysis of light bulb production suggested that there was a relationship between the quality of the product and the manufacturing which was adopted.[3] A similar relationship was also implied between the quality of inputs and the production technique.[4] However, there was no quantitative analysis of these relationships.

2. Shipbuilding Industry

The Beazer, Cox and Harvey[5] study of the US shipbuilding industry examined capital labor and investment/worker ratios

[1]Gold, *et.al,* pp. 40-41 recognize that innovations may directly affect the qualitative characteristics of both inputs and outputs.

[2]James R. Bright, *Automation and Management,* Graduate School of Business Administration, Harvard University, 1958.

[3]*Idem.*, p. 26.

[4]*Idem.*, p. 138.

[5]William F. Beazer, William Cox and Custis A. Harvey, "US Shipbuilding in the 1970s," Lexington, Mass., Lexington Books, 1972.

over a number of years. The study compared characteristics of the US shipbuilding industry with features of the same industry in other countries, and incorporated an analysis of the technology used in the shipbuilding process.[1] Since there was no intent in the study to demonstrate that production processes may change when the quality of the product is varied, there is no analysis of the technological changes which have occurred over time.

3. Computer Industry

Harman[2] conducted an intensive analysis of product innovation in the computer industry. He measured the capabilities of computers on the basis of the computer's central processor speed, the time the processor is idle waiting for information, and the memory capacity.[3] The actual and Harman's estimated values of computer performance are displayed in Figure 2. The evidence (as is well known) demonstrates a tremendous growth in the performance of computers. However, Harman did not seek to relate these product characteristics to production processes or input requirements.

Chow's[4] study of the technology and demand for computers also did not address that question, but his approach solved the problem of aggregating distinct computers, each of which had differing qualities or characteristics.[5] Chow assumed

[1] *Idem.*, pp. 27-38 and pp. 141-146.

[2] Alvin J. Harman, *The International Computer Industry: Innovation and Comparative Advantage*, R-474-PR, Santa Monica, CA, The RAND Corporation, 1971.

[3] *Idem.*, p. 70. This measure is derived from K.E. Knight, "Changes in Computer Performance: A Historical View," *Datamation*, 12, No. 9, September 1966, pp. 40-54.

[4] Gregory C. Chow, "Technological Change and the Demand for Computers," *American Economic Review*, LVII, No. 5, December 1967, pp. 1117-1130.

[5] Gold has argued that technological change studies could not use a production function approach because neither the input nor output could be aggregated due to quality differences.

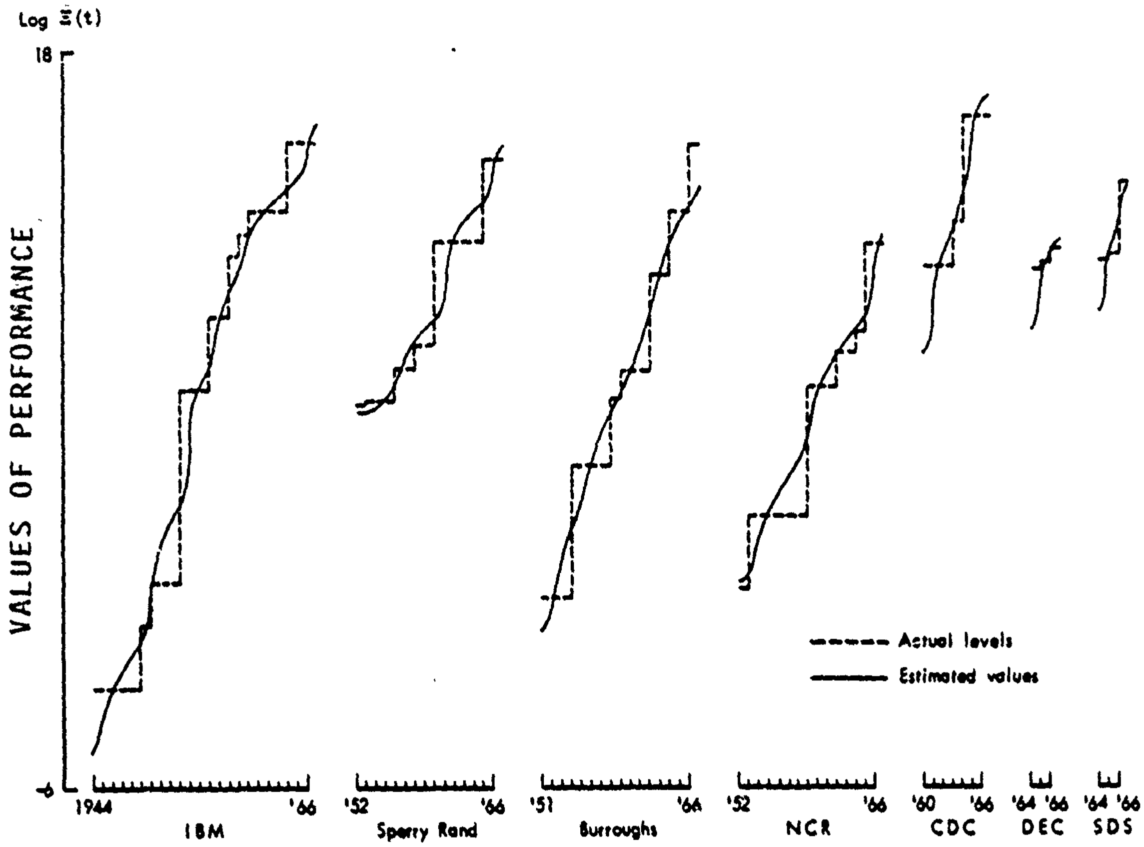

Figure 2. ACTUAL AND ESTIMATED VALUES OF COMPUTER PERFORMANCE

Source: Harman, *op.cit.*, p. 91.

that computers, regardless of the specific qualities, can be grouped as a single good. The quantity of this computer good was measured as the real rental value that a specific system would realize. In turn, the rental value of any specific system was a function of its characteristics, namely, multiplication speed, memory size and access time.[1] After calculating the "quantity" of computers in existence (based on

[1]This transforms the characteristics of a multidimensional product to a single index, its rental value.

the performance characteristics), Chow demonstrated that the price of computers, when their quality attributes were taken into account, declined nearly 90 percent between 1954 and 1965. This statement does not mean that a computer actually being sold (rented) in 1965 had a price only 10 percent of the selling (rental) price of a 1954 computer;[1] the newer computer would perform more and might actually cost more in constant dollars than the older system.[2]

4. Automobile Industry

Abernathy[3] analyzed the productivity and innovations of the Ford Motor Company; he considered both product and process innovations on the assembly line and in the engine plant. He concluded that the efforts to improve productivity often limit the ability to change the products or process. This is the result of introducing an equipment-intensive structure into the manufacturing process; consequently, it is difficult to make even minor changes without affecting the entire process.[4]

Although Abernathy explicitly recognizes the interaction of the product and process innovations, there is no attempt to describe in detail the extent to which quality changes have

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[1]This decline occurred despite an approximate 20 percent increase in the GNP inflator over the same period.

[2]Unfortunately, neither Harman nor Chow provide the actual rental or sales prices. On the other hand, Sharpe had concluded that the costs of producing a computer with *specific fixed* capabilities fell about 20-25 percent per year through the 1960s. William F. Sharpe, "The Economics of Computers," Columbia Univ. Press, N.Y., 1969, pp. 262 and 353.

[3]William J. Abernathy, "The Productivity Dilemma," Johns Hopkins University Press, Baltimore, 1978.

[4]*Idem.*, p. 69. However, this result may not hold universally. Foreign automobile manufacturers have introduced product innovations using processes similar to those utilized in the US.

affected production costs.[1] Data are presented which show the numbers of labor hours utilized in engine manufacture and final assembly but these data are not adjusted for quality changes in either the inputs or the output.[2] The available data (see Figures 3 and 4) show the effects of learning, but also demonstrate that the introduction of a new process may raise costs substantially.

5. Petroleum Industry

Enos[3] undertook a very careful study of process innovation in the petroleum industry. He traced the development of the various techniques which have been used to refine crude oil into such final products as gasoline, kerosene, etc. The analysis of production processes involving a homogeneous product, such as oil, is considerably less complicated than the study of production functions for outputs, which over time exhibit fundamental changes in their attributes. This may explain why Enos' study provides such an excellent *explicit* documentation[4] of the relationship between production costs and technological change.[5] However, even in this case it was

[1]For example, Abernathy shows that the assembly labor content per car has remained relatively constant from the 1920s to the 1970s. Part of this is attributable to less subcontracting and the greater complexity of the newer cars. *Idem.*, p. 158. However, Abernathy does not adjust the data for these factors. Moreover, it is also possible that the composition of the workforce might have changed over time. Abernathy recognizes that non-salaried labor hours in engine manufacturing are not identical to production labor, but time trends in the use of different types are not presented.

[2]*Idem.*, pp. 156-159.

[3]John L. Enos, "Petroleum Progress and Profits," Cambridge, Mass. Massachusetts Institute of Technology Press, 1962.

[4]*Idem.*, pp. 246-258.

[5]On the other hand, Bright (*op.cit.* pp. 9-10) indicated that few executives were able to provide any data about the cost savings that automation had provided to their own plants.

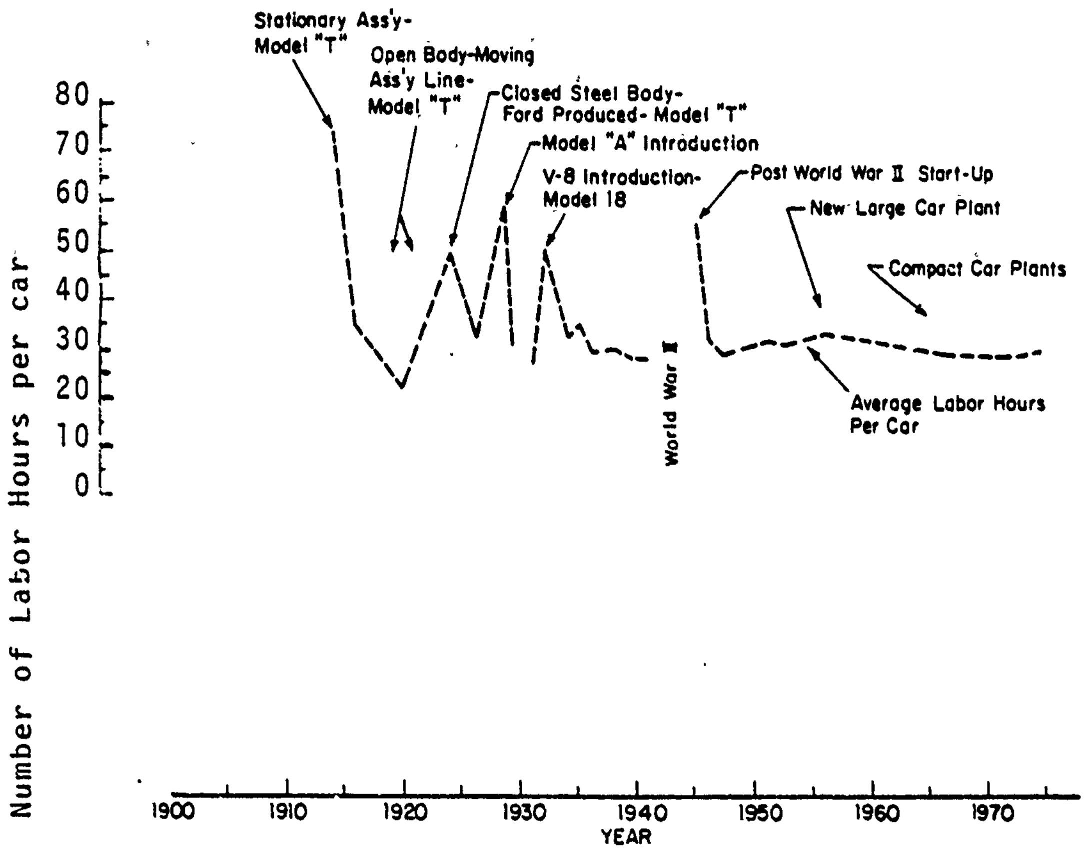

Figure 3. ASSEMBLY LABOR HOURS PER CAR 1900 - 1970
Source: Abernathy, *op. cit.*, p. 159

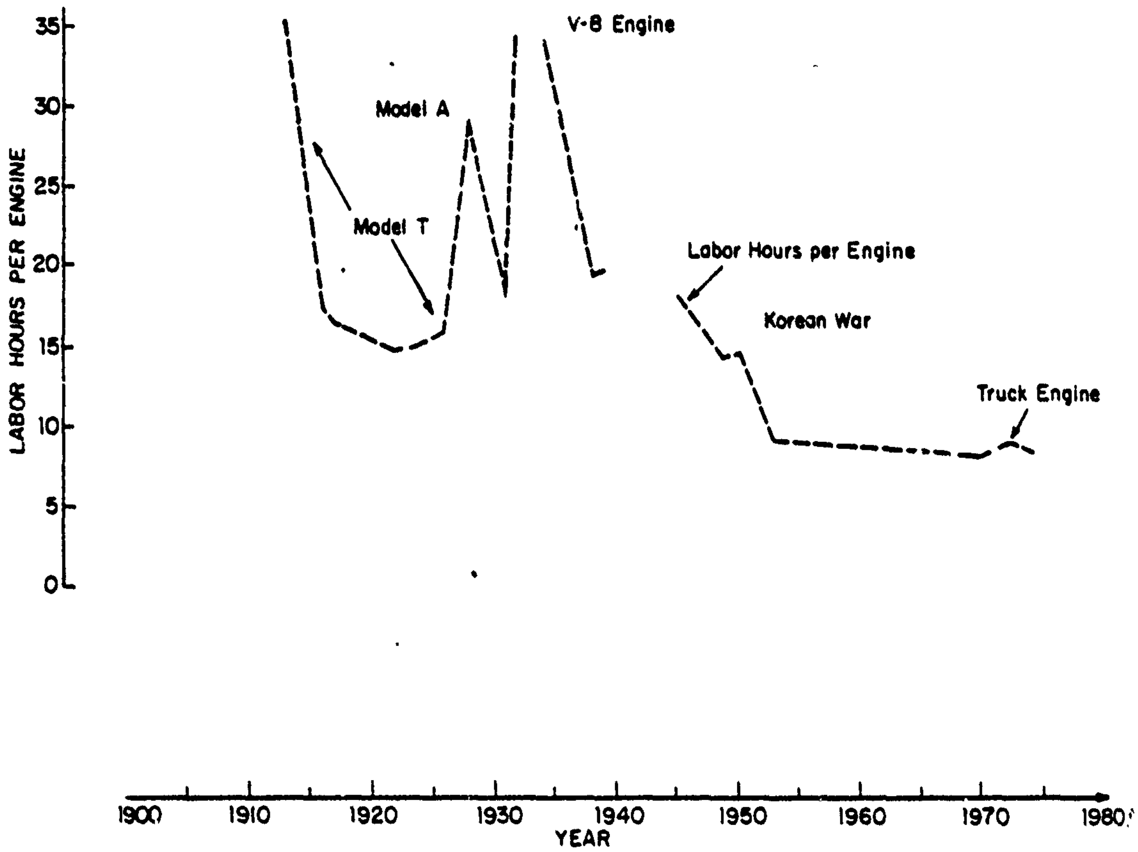

Figure 4. LABOR HOURS PER ENGINE 1900 - 1980

Source: Abernathy, *op. cit.*, p. 156.

necessary to adjust the costs for changes in the quality of gasoline as measured by the octane ratings. Hence, some of the decreased real costs holding quality constant would not actually have been observed at the pumps because the public obtained a higher quality gasoline. Figures 5 and 6 show how the productivity of labor and capital increased with the introduction of a succession of new processing innovations.[1] Naturally the obverse of this relationship would show declining costs for producing a given level of quality adjusted output.

6. Steel Industry

There have been a number of studies of the Basic Oxygen Furnace (BOF) process for making steel.[2] From these studies it has been possible to derive the cost savings that would result from the replacement of open hearth furnaces with the new BOF process. It is possible to obtain those figures because steel is a relatively homogeneous product. There are quality variations in the alloy content of steel, but Rosegger's latest study of the BOF process does not directly analyze the relationship between costs and the quality of the product.[3]

C. SUMMARY

A number of studies have examined processes and product innovations in specific industries. Enos' study of the petroleum industry provides explicit answers to the questions which

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[1]Enos also presents similar data for energy and raw material inputs.

[2]See Gerhard Rosegger, "Basic Oxygen Furnace: Technological Characteristics and Expected Economic Effects," in Gold, Rosegger, and Boyle, *loc.cit.*, for a bibliography.

[3]Such an analysis would have shown how technological change which affects product qualities also affects costs.

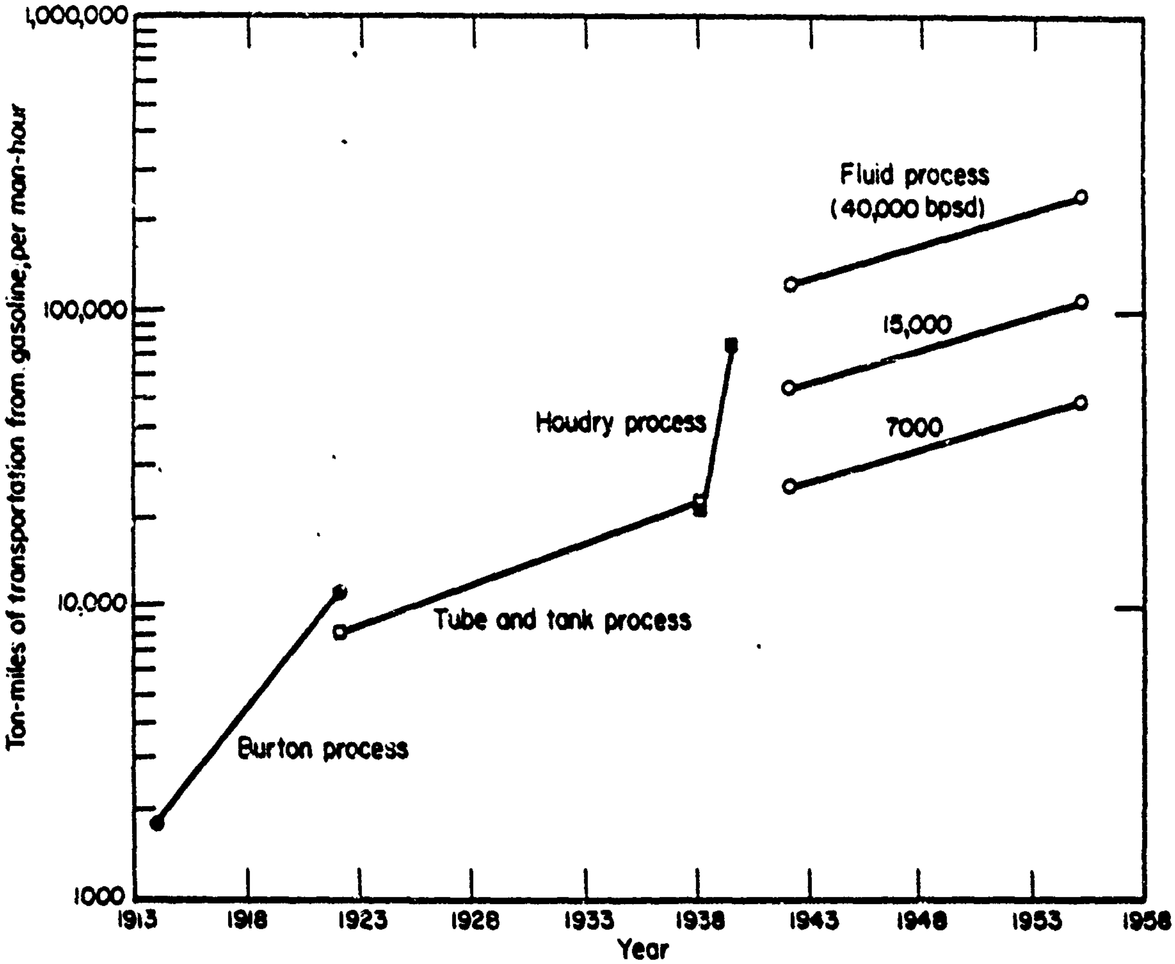

Figure 5. PRODUCTIVITY OF PROCESS LABOR IN CRACKING

Source: Enos, *op. cit.*, p. 247.

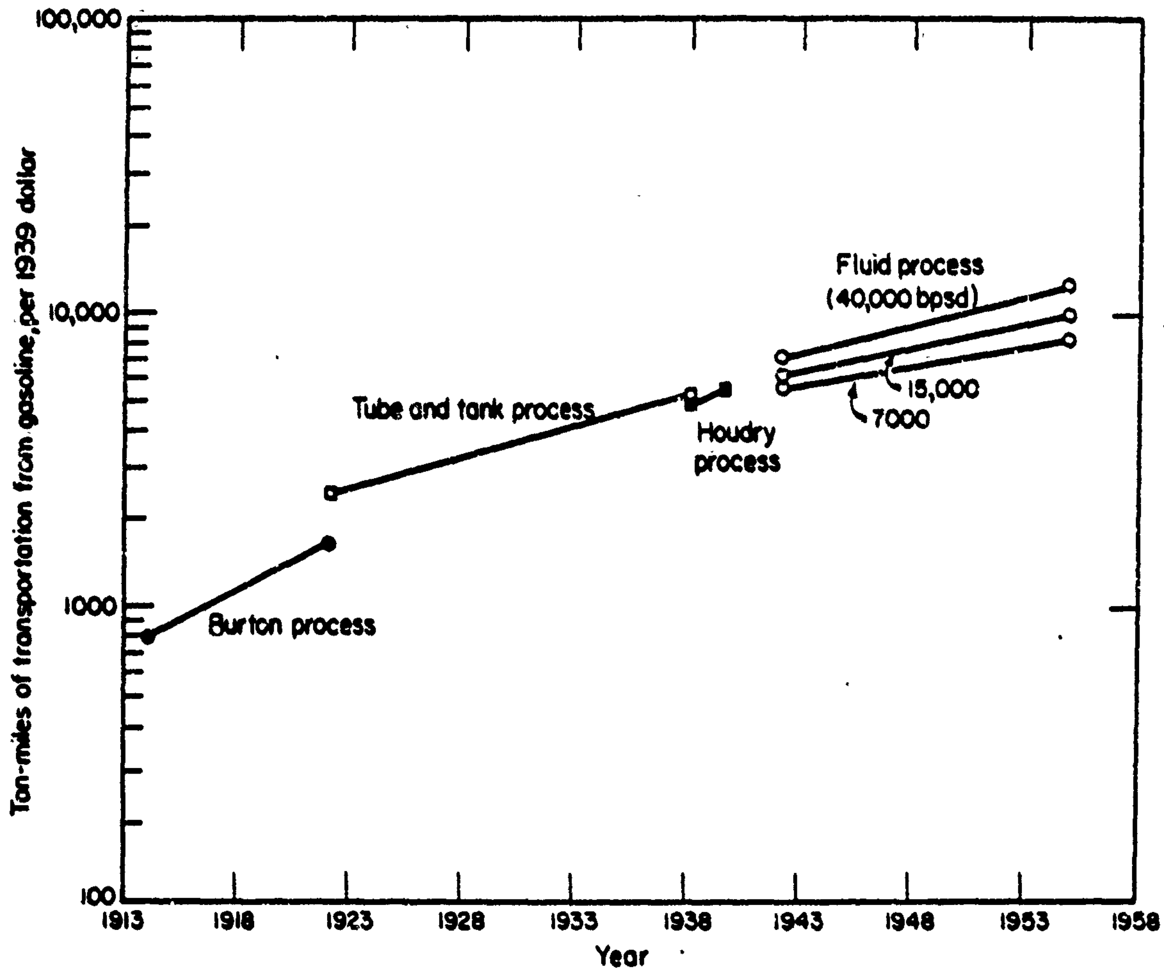

Figure 6. PRODUCTIVITY OF CAPITAL IN CRACKING

Source: Enos, *op. cit.*, p. 248.

concern us. That study showed how production costs were related both to the quality of the product and the process innovations which occurred. Petroleum is a relatively homogeneous product and this may explain why it was possible to obtain explicit data.[1] It may have been much more difficult to document these data for a product such as an automobile which has multi-dimensional characteristics.

Using these findings and methodologies as background, we now turn our attention to the technological changes which have occurred in the aerospace industry.

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[1]The availability of data for the steel industry seems to corroborate this view. It may be possible to derive process (i.e., engineering-based) models of the production flow for each homogeneous product. See A.A. Walters, "Production and Cost Functions: An Econometric Survey," *Econometrica*, January-April 1963, pp. 1-66. Process type models have also been used in a different context by Barry Bosworth, *Capacity Creation in Basic Materials Industries*, Brookings Economic Paper, 1976, #2, pp. 297-341.

Chapter V

TECHNOLOGICAL CHANGE AS REFLECTED IN THE QUALITY OF FIGHTER AND ATTACK AIRCRAFT

Chapter IV considered the difficulties that were involved in analyzing technological changes in terms of its two components, production processes and product qualities. The best estimates of cost reductions attributable to technological change were derived for industries where the product was relatively homogeneous. We now turn to an analysis of some of the technological changes which have occurred in segments of the aerospace industry over the period 1960-1980. In this chapter we present a variety of measures which provide information about changes in the performance characteristics of military combat aircraft.

A. GENERAL MEASURES OF QUALITY CHANGE

In a previous study, Stekler identified some trends which had occurred in the aerospace industry up to the early 1960s.[1] That study indicated that the military products of the industry were becoming increasingly complex.[2] This was measured by (1) the ratio of research and development costs to total system costs, and by (2) the number of electronic components contained within various weapons systems. Our

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[1]Herman O. Stekler, "The Structure and Performance of the Aerospace Industry," University of California Press, Berkeley, 1965, pp. 1-24.

[2]*Idem.*, pp. 18-19. That study used data obtained from Merton J. Peck and F.M. Scherer, "The Weapons Acquisition Process," Harvard Univ. Press, Cambridge, 1962.

analysis first determines whether these trends continued through the 1970s.

1. Research and Development Expenditures

The earlier analysis of research and development expenditures relative to procurement costs included a sample of both bombers and fighter aircraft. The R&D expenditures were compared with total system costs and not with procurement costs for a specified quantity of aircraft. Consequently, if the same amount of R&D expenditures had been expended, but the total buy had been changed, the ratio of R&D outlays to total costs would have been altered.

The subsequent analysis uses data only for fighters, fighter-bombers, and attack aircraft. Moreover, the comparison of R&D costs and procurement costs is standardized across all aircraft. The costs in this analysis refer only to *airframe outlays*, and the research and development costs are compared with the airframe costs associated with the procurement of the first 100 aircraft of each type.

Several comments are required at this point. First, the data which are used were derived from a study prepared by J. Watson Noah Associates, Inc.[1] Second, the Noah data are divided into the categories non-recurring and recurring costs; we associate the former with R&D costs and the latter with procurement costs. Finally, some of the non-recurring costs are derived by an innovative statistical technique since the cost data were not available by these classifications for the earlier airframes.

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[1]J.W. Noah, J.M. Daniel, C.F. Day, and H. L. Eskew, *Estimating Aircraft Acquisition Costs by Parametric Methods*, J. Watson Noah Associates, FR-103-USN (abridged), September 1973.

Table 7 presents the total, non-recurring, and recurring cost data for the airframes of fighters and attack aircraft. The aircraft are listed sequentially according to the date of delivery of the first production units, encompassing the period 1947-1972. All dollars have been converted into 1970 constant dollars.

First, there is an upward trend in the total cost (in real dollars) of developing and procuring the airframes of the first 100 units of each type. Although the trend is not monotonic, on average, the first 100 airframes of the newer types of fighter and attack aircraft cost more than earlier models.[1]

Second, it should be noted that the non-recurring costs as a percentage of total costs are higher *on average* for the later model aircraft than they were for the earlier aircraft. While the result is not true for every individual type, the discrepancy may be the result of the estimating techniques used by Noah Associates to divide the known total costs into the separate categories, recurring and non-recurring.[2] Despite the absence of a uniform trend, the evidence is sufficiently strong to suggest that, for a standardized quantity, non-recurring costs over time have become a larger percentage of total costs.

[1]The data for the A-7A/B are not consistent with the statement. However, it must be remembered that the A-7 was developed from the F-8 which is not included in the Noah data set. (In fact, RAND now does not include the A-7 in its data base as a new model aircraft.) The F-5 is also not included in the Noah data set.

[2]In a later study, Noah Associates replaced the recurring/non-recurring dichotomy with a different classification scheme. Costs were now divided into the categories of design and production. The former included system development cost (both recurring and non-recurring) and engineering costs for test airframes. This newer dichotomy differs from conventional definitions including the *Cost Information Reports* and appropriations categories. Unfortunately, Noah did not publish data, similar to those presented here, using the new categories.

Table 7. TOTAL, NON-RECURRING, AND RECURRING COSTS OF THE FIRST 100 AIRFRAMES OF VARIOUS FIGHTER AND ATTACK AIRCRAFT

Aircraft	Total	Non-Recurring Costs (Millions of 1970 $)	Recurring Costs	Non-Recurring Costs as a Percentage of Total Costs
F-84	96.7	10.7	86.0	11.1
F-86	103.7	16.7	87.0	16.1
F-86D	159.2	34.2	125.0	21.5
F-3	293.7	63.7	230.0	21.7
F-89	231.4	17.4	214.0	7.5
A-3	371.	34.0	337.0	9.2
F-100	209.2	59.2	150.0	28.3
F-101	421	81.0	340.0	19.2
A-4	n.a.	n.a.	173.0	n.a.
F-102	554.	184.0	370.0	33.2
F-104	257.5	47.5	210.0	18.4
F-105	683	153	530.0	22.4
F-106	590	200	390.0	33.9
A-5	722	222	500.0	30.7
F-4	606	146	460.0	24.1
A-6	n.a.	n.a.	215.0	n.a.
A-7A/B	158	35	123.0	22.2
F-111	1395.9	395.9	1000.0	28.4
F-14	899	269	630.0	30.0

Source: J.W. Noah, J.M. Daniels, C.F. Day, and H.L. Eskew, *Estimating Aircraft Acquisition Costs by Parametric Method;* J. Watson Noah Associates, Alexandria, VA, September 1973, FR-103-USN, pp. 33-34.

These two pieces of evidence suggest that aircraft have become more complex. First, the real total costs of the first 100 airframes of successive models of fighter and attack aircraft have increased with time. Second, non-recurring outlays (which are a proxy for R&D expenditures) have become a larger percent of those total procurement costs.

2. Electronics Components

There is another and more direct measure of the increased complexity of combat aircraft--the electronics content and subsequent costs of these aircraft. One estimate was that the average electronics fraction of total aircraft cost has increased from between 10 and 20 percent in the 1950s to between 20 and 30 percent by the early 1970s.[1] Another measure of this increased electronics content is the weight of avionics equipment installed in various types of attack and interceptor aircraft. Figure 7 shows a clear trend in the installed weight of avionics system; avionics in the F-86 weighted 200 pounds, in the F-14 the installed weight was between 3,000 and 4,000 pounds.

This increase in installed weight occurred despite the spectacular technological breakthrough in electronics which substantially increased the number of functions that could be performed per pound of equipment. The improved equipment performance resulted from new technologies such as the transistor, large scale integration and miniaturized assemblies. One such estimate of the functions per pound of equipment is presented in Figure 8.

[1]Howard P. Gates, Barry S. Gourary, Seymour J. Deitchman, Thomas C. Rowan and C. David Weimer, *Electronics-X: A Study of Military Electronics With Particular Reference to Cost and Reliability*, Report R-195, Institute for Defense Analyses, Arlington, VA, January 1974, pp. 56, 154 and 377; see also *Aviation Week & Space Technology*, March 11, 1974, pp. 107-109.

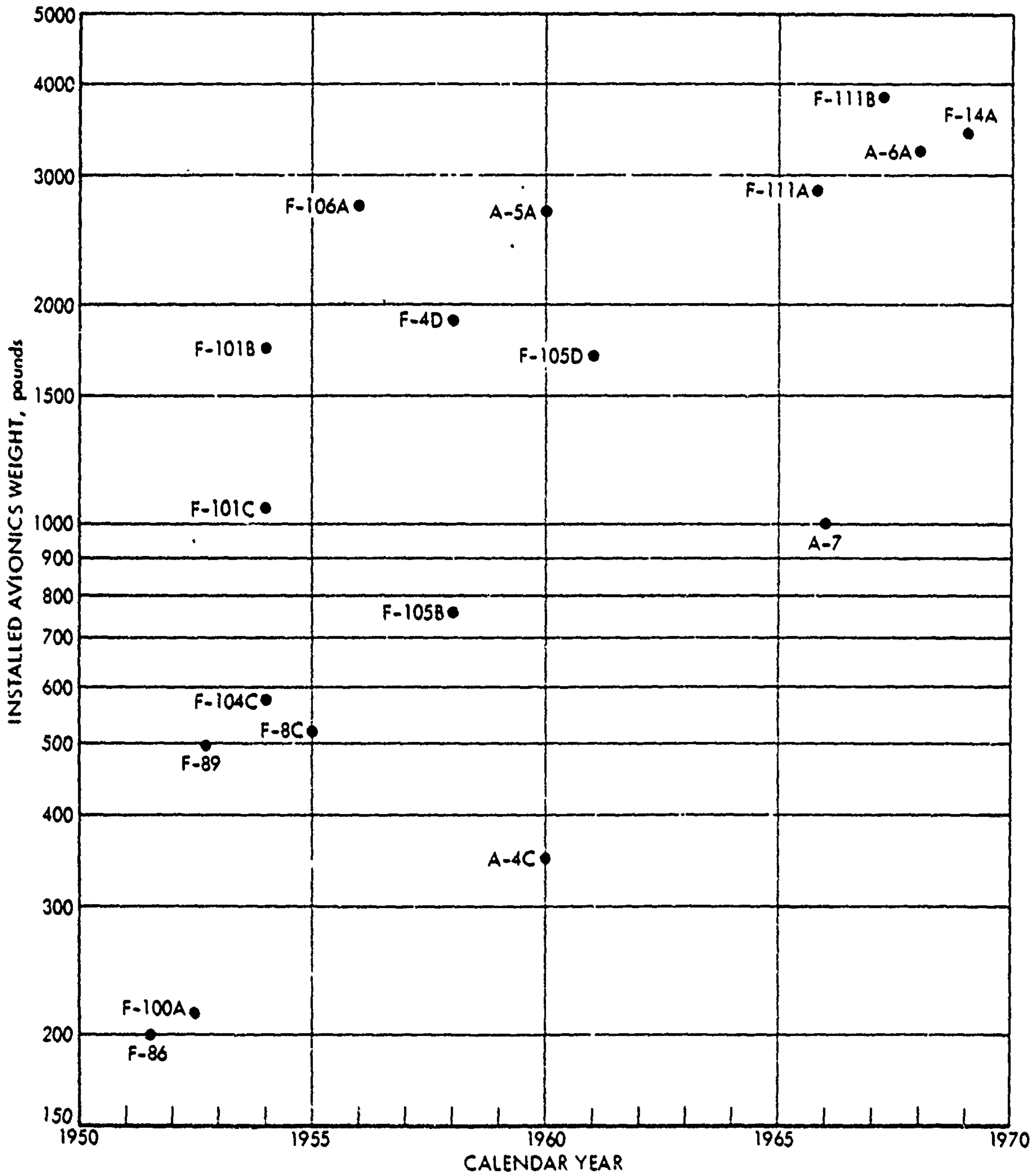

Figure 7. AVIONICS SYSTEM WEIGHT TREND IN ATTACK AND INTERCEPTOR AIRCRAFT

Source: Gates, *et al.*, *op. cit.*, p. 57.

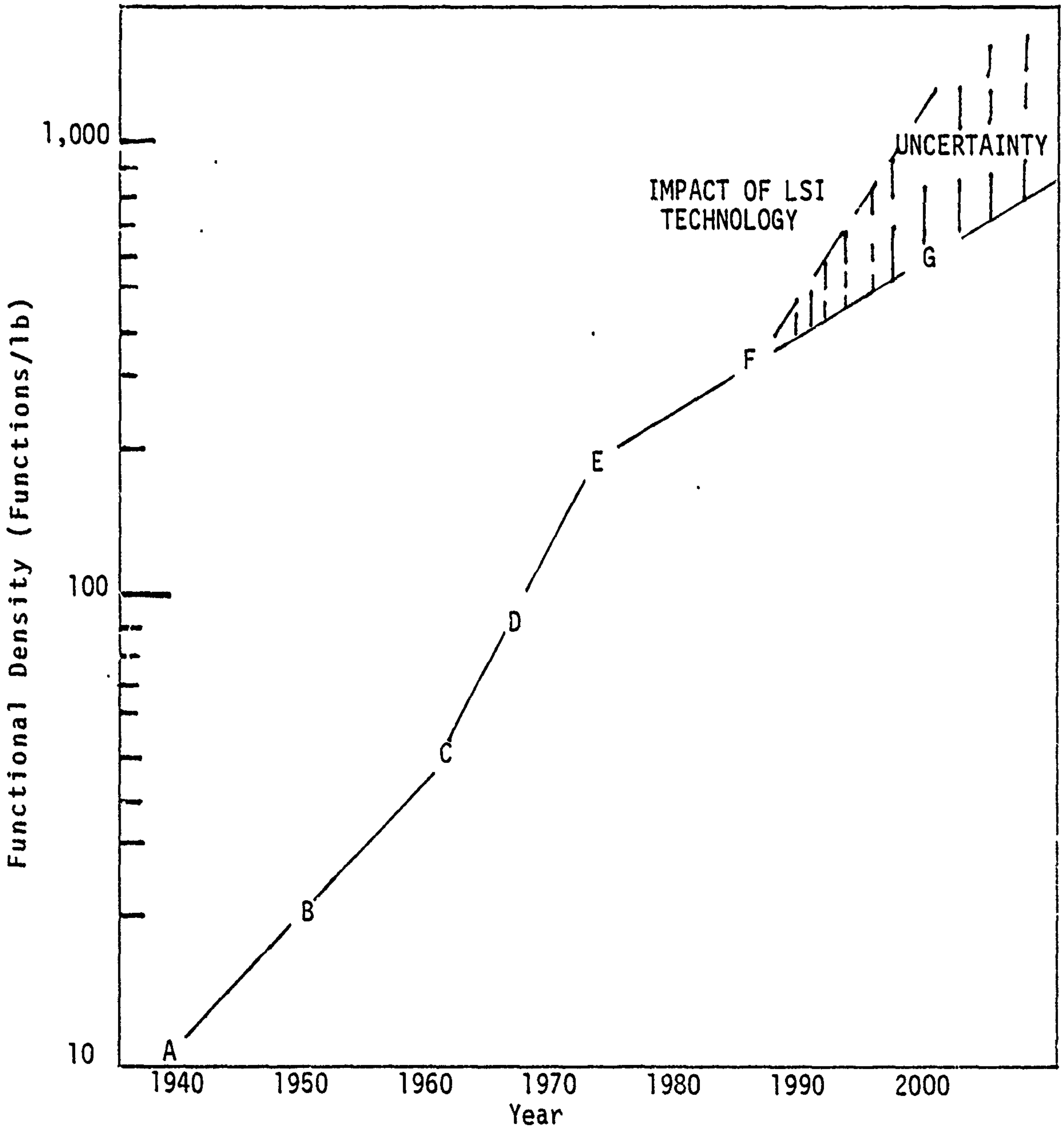

Figure 8. AVIONICS BENEFIT FROM THE ADVANCE OF ELECTRONIC-CIRCUIT TECHNOLOGY

Source: *Aeronautics and Astronautics*, June 1979, p. 34.

It is obvious that increased installed avionics weight concomitant with an increase in the functional capabilities implies that more functions were required of the electronics equipment. This indicates quite clearly that the complexity of combat aircraft has increased with time.[1]

B. SPECIFIC QUALITY CHANGES ASSOCIATED WITH FIGHTER AND ATTACK AIRCRAFT

The previous discussion of the quality of modern combat aircraft dealt with relative intangibles such as complexity. There are direct measures of the performance that can be obtained from combat aircraft which include--

- Max speed
- Cruising speed
- Combat ceiling
- Payload
- Range
- Rates of turn and climb
- Take off distance
- Landing distance
- Landing speed
- Endurance.

Table 8 presents information about the characteristics associated with a number of combat aircraft which were operational in the 1960s and 1970s. The data show that in some dimension the performance of the aircraft increased, i.e., they either fly faster, higher or carry heavier payloads for

[1]DoD might not have benefitted from the decreasing cost of electronics that has been observed in other markets, for the military requires specialized equipment in relatively small quantities. This implies that the military must pay for the high costs of special designs, small production runs and special quality control. See Gates, *et.al.*, *op.cit.*, *Electronics-X:* pp. 64-138.

Table 8. PERFORMANCE CHARACTERISTICS OF SPECIFIED FIGHTER AIRCRAFT

	F-105	F-4B	F-4E	F-4F	F-4J	F-111	F-14	F-15	F-16	F-18
Max Speed (mph or Mach)	1485 m2.1	m2+	m2+ 1500	m2+	m2+	*1650 m2.5	*1320 m2.4 (design)	*1320 m2.5	m1.95-2+	m1.8-m.2
Cruising Speed (mph or Mach)	M0.4-0.95	580	571				460-633			
Ceiling (ft.)	50,000	71,000	54,400-71,000	71,000	71,000	*60,000+	56,000+	100,000 (absolute)	50,000+	50,000
Payload (lb.)	12,000	16,000	16,000	16,000	16,000		17,000	15,000	15,200	13,700
Range (Nautical miles)	1,797	,000	2,600	2,000	2,000	*3,300+		3,000	2,000+	2,000+
Take-off dist. (feet)	2,000	5,000	5,880	4,850	4,540	3,000	1,200	900	1,750	800
Landing dist. (feet)	4,960	3,000	5,690	5,430	5,430	3,000	1,500	2,500	2,550	1,800
Landing speed (mph)		150	150	150	150			144		150

Source: Various Issues of Jane's (see 68-69 for F-111, 79-80 for F-14, F-15 speeds) *Jane's Pocket Book of Combat Aircraft a longer distance. Moreover, both the takeoff and landing distances have been reduced.

In order to achieve these performance characteristics, a number of aerodynamic design changes were introduced including--

- Changes in the wing design to reduce drag at supersonic speeds.[1]
- Introduction of new metals and materials to withstand the heat generated by supersonic speeds.
- Development of the variable sweep wing.
- Increase in the operating temperatures of aircraft engines, thus requiring new materials with different temperature, strength, and weight characteristics.[2]
- Development of engine inlets that permit aircraft to operate efficiently over broad flight spectra.

The aerodynamic design changes which helped to produce some of the observed performance characteristics sometimes required changes in manufacturing technology and/or production inputs. In the next chapter we shall examine how the methods of producing military aircraft changed over the past two decades.

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[1]*Astronautics and Aeronautics*, March 1980, p. 31

[2]*Aviation Week and Space Technology*, June 22, 1970, p. 27.

Chapter VI

THE RELATIONSHIP BETWEEN QUALITY CHANGE AND AIRCRAFT PRODUCTION TECHNOLOGY

Chapter V discussed the fact that changes in manufacturing technology and/or production inputs were required because of the new designs and performance characteristics of fighter aircraft. This chapter will examine these changes. It will focus upon changes in both the number and types of inputs, namely, materials, capital and labor. This chapter will also analyze the production interrelationships between these various inputs.

It is first necessary to characterize the production processes of this industry and to distinguish the process of manufacturing military aircraft from the techniques used in other industries.

A. PRODUCTION PROCESSES

A simplified description of industrial processes suggests that they can be divided into three categories: (1) continuous processing, (2) high volume mass production of discrete items, and (3) low volume batch processing of individual items.[1] The first classification consists of manufacturers, such as oil refiners, who produce a continuous stream of goods which are indistinguishable from each other. The production processes are highly automated.[2]

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[1]Controller General of the United States, General Accounting Office, *Manufacturing Technology - A Changing Challenge to Improved Productivity*, LCD-75-436, June 3, 1976, p. 20.

[2]*Ibid.*

The discrete parts' manufacturers "change the shape of materials to produce discrete components that are assembled into functional end products."[1] These products may be produced in large volume with mass production techniques or in smaller amounts using batch processes. The mass production techniques are characterized by high mechanization which is relatively inflexible.[2] On the other hand, with batch processes the volume is low, products are not standardized, and the machinery must be extremely flexible. General purpose equipment would be used to produce a variety of parts.

About 75 percent of all metal working items are produced in the batch mode, and the technology of the military aircraft industry must be placed in this category. At present these aircraft are produced at the rate of only 1 to 4, 6 or 8 per month, depending on the particular model. This consideration must be kept in mind in all subsequent analyses of the production process. The introduction of mass production techniques is not to be expected. When new machinery is introduced, it is likely to be flexible and adaptable.

B. NEW MATERIALS

One of the major technological advances in the military aircraft industry has been the introduction of new materials from which the structural components of the aircraft have been fabricated. The major new materials used in these aircraft are titanium and composites. In turn, the increased use of these new materials has required new manufacturing and fabrication techniques and machinery.

[1] *Ibid.*

[2] *Idem.*, p. 21. Abernathy's study of the automobile industry made a similar point.

1. Titanium

An increasing percentage of the weight of military aircraft airframes consists of structural components fabricated from titanium. For example, 9 percent of the F-4 airframe weight consisted of parts made from titanium. This rose to 25 percent for the F-14 and 34 percent for the F-15.[1] An increasing amount of titanium has been incorporated into airframes because of the properties of the metal which combines high-strength, temperature resistance, and relatively low weight.[2]

While titanium has characteristics which make it desirable for use in parts to be incorporated into the airframes of combat aircraft, it is a metal which proved difficult to handle in the manufacturing process. New procedures for handling titanium and titanium alloys had to be developed for all the traditional metal processing techniques including riveting, welding, cutting, chemical milling, bonding and casting.[3] For instance, casting titanium was considered difficult because the metal was reactive. On the other hand, it was considered especially important to learn to cast complex parts from the metal because the forging and subsequent machinery procedures were so expensive.

An example illustrates how expensive it is to machine a titanium part. The center fuselage bulkheads for the F-15 are made from titanium and are machined from metal forms delivered to McDonnell-Douglas. The delivered weight of the metal from

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[1] *Aviation Week and Space Technology*, January 26, 1976, p. 33.

[2] *Aviation Week and Space Technology*, November 20, 1967, pp. 228-235.

[3] For information about the problem that the aerospace industry encountered in the manufacturing process of parts made from titanium see the following issues of *Aviation Week and Space Technology*, Dec. 2, 1963, 48-61; Dec. 9, 1963, pp. 98-111; Mar. 10, 1966, p. 45; Aug. 29, 1966, p. 97; Sept. 19, 1966, p. 105; Nov. 6, 1967, p. 47; Dec. 16, 1968, pp. 41-43; Nov. 24, 1969, p. 32; and July 19, 1971, pp. 52-54.

which the lower bulkhead is machined is 1,250 pounds. The finished bulkhead, after milling, weighs only 145 pounds. Similarly, the upper half of the bulkhead weighs 100 pounds; it is machined from titanium forms weighing 900 pounds.[1]

The introduction of titanium and the development of new manufacturing processes required the development of new metal working machinery. This aspect of the change in production technology will be discussed in a later part of this chapter.

2. Composites

Composite materials are polymeric or metal matrices reinforced with fibers or filaments. There are many such reinforcing agents including boron, carbon, glass-fiber mixtures and graphite.[2] The advantages of these new materials are greater strength, less fatigue, non-corrosion and lower weight. It has been estimated that components made from these composites weigh 20 to 70 percent less than similar components made from titanium.[3]

One of the main disadvantages of these materials is their expense. At present, structures made from some of the newer composites would not be competitive in price with metal structures or even with some of the older composites such as carbon-epoxy. However, the composite materials might have lower scrappage rates.

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[1] *Aviation Week and Space Technology*, Oct. 29, 1973, p. 48.

[2] Information about the use of the composite materials was obtained from the following issues of *Aviation Week and Space Technology*, March 17, 1968, pp. 46-52; May 27, 1968, pp. 61-70; June 3, 1968, pp. 49-74; Aug. 18, 1969, pp. 51ff; June 22, 1970, pp. 29-41; July 12, 1971, pp. 47-49; July 15, 1974, pp. 15 and 235-238; January 26, 1976, pp. 73-77 and 123-125; and January 8, 1979, pp. 35-41.

[3] It is also possible to construct a portion of the airframe using a smaller number of components then are required using a metal structure. *Aviation Week and Space Technology*, Jan. 13, 1975, p. 39.

The F-14 was the first aircraft designed from the start to use composite materials. There, boron-filament reinforced epoxy sheets are used as the outer skins of the horizontal stabilizer.[1] Currently, composite materials account for about 10 percent of the structural weight of the F-18.[2]

Again the manufacturing techniques utilized to fabricate components made from these materials were affected. Here, however, the main problem appears primarily to be the cost of tooling required to manufacture the items.[3] Generally, large integrated unitized components are manufactured by hot pressing. This procedure generally requires expensive tooling such as the matched die sets required for pressing under high pressures.[4]

C. CAPITAL EQUIPMENT AND MANUFACTURING TECHNOLOGY

The higher performance requirements of modern aircraft could only be attained by using newer metals, alloys and materials. In addition, some of the structural components of these aircraft have become more complex and closer tolerances have been required. These technological changes in the design of the aircraft, in turn, have necessitated the development of new capital equipment[5] and manufacturing

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[1] *Aviation Week and Space Technology,* March 17, 1969, p. 46.

[2] *Astronautics and Aeronautics,* March 1980, p. 33.

[3] It had earlier been suggested that composite materials could not be machined by cutting. The heat generated by the machining process could melt the plastic matrix of a composite. See *Aviation Week and Space Technology,* April 22, 1968, p. 61.

[4] *Aviation Week and Space Technology,* September 11, 1972, p. 90; January 26, 1976, p. 75; April 19, 1976, p. 17; and January 8, 1979, p. 40.

[5] Moreover, these capital goods are now company-owned rather than furnished by the government.

technology.[1] These manufacturing techniques can be grouped into three categories--traditional machining, non-traditional machining, and forming.[2]

1. Traditional Machining Methods

The traditional method of machining an item was to remove material in the form of chips by using a cutting tool on a metal work piece. This operation was usually performed manually by a skilled craftsman operating one of a number of different types of machine tools. However, the more complex parts of the newer aircraft required three dimensional machinery with closer tolerances than could be attained with a manually operated tool. Consequently, the numerically controlled (NC) machine tool was introduced in 1956.

A NC machine is a tool controlled by an electronic unit which receives coded instructions, usually from a punched tape, and directs the tool's motions. Thus the machine's actions are under automatic control, and the successive items produced by that tool using that procedure will be virtually identical. The use of NC tool not only simplifies the production process and assures that the tolerance requirements will be met, but also has an impact upon subsequent assembly procedure because all parts are identical.

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[1]However, this study does not attempt to discriminate between those changes in production techniques resulting from technological change and those attributable to changes in factor prices.

[2]Information about the newer manufacturing techniques used in the aerospace industry were derived from *Aviation Week and Space Technology*, April 15, 1968, pp. 56-82; April 22, 1968, pp. 48-61; April 29, 1968, pp. 99-105; June 22, 1970, pp. 232-242; January 26, 1976, pp. 81-82; October 16, 1978, pp. 16-21; Oct. 30, 1978, pp. 42-46; November 20, 1978, pp. 44-55. Also from the GAO report, *Manufacturing Technology - A Changing Challenge to Improved Productivity, op. cit.* pp. 26-39.

The early NC machines controlled only one tool; later versions, known as machining centers, had several different types of tools built into one machine. These machines automatically selected a tool, performed the necessary cutting operations, and then replaced the tool.

The newest automatic tools are still more sophisticated. They are directly controlled by small computers rather than by punched tape.[1] Moreover, some of the machines are also equipped with adaptive controls to optimize cutting speeds. The controls have sensors which determine the hardness[2] of the material on which work is being performed; this is an especially important characteristic when composite materials are utilized.

The use of computers, etc., to replace the tapes which formerly drove the tools saves time, since the machines do not have to be reprogrammed after every batch job. Moreover, it is now possible to combine the design and manufacturing engineering functions. This coordination has been designated Computer Aided Design and Computer Aided Manufacturing (CAD/CAM) and will be discussed below.

2. Other Types of Cutting Methods

The aerospace industry has also developed (and improved) other methods for cutting the newer high strength materials.

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[1]This is more efficient because the machine does not have to retrace the entire sequence of operations if a particular error occurs.

[2]The hardness of titanium and steel require slower cutting rates. Even then the tools wear out at faster rates than when aluminum is used.

These materials are especially difficult to process if the components have complex shapes or are thin walled.[1] These other methods can be divided into three categories, chemical milling, electrochemical machining and electric discharge machining. Chemical milling was first used in World War II and has subsequently been improved. It is a method for removing metal by dissolving it in a chemical bath. Electrochemical machining has been used to drill relatively small deep holes in nickel and cobalt super alloys. This type of machining is a deplating process in which metal is removed from a workpiece and flushed away by an electrolyte.[2] Electric discharge machining can produce complex shapes from refractory metals and alloys which were once thought to be unmachinable. Material is removed by a series of short electrical discharges between an electrode and a workpiece.

3. Forming

Forming originally was not as important as machining among the aerospace industry's manufacturing techniques. Currently, the process of producing parts by pressing and forging is receiving greater attention. These forming processes save both materials and machining time and produce parts which are near-net shape, i.e., very close in form to the required final product.

The greater interest in producing near-net shape parts was stimulated by the high and rising costs of the newer metals. Using the traditional methods of producing aircraft parts, ten pounds of metal inputs were often required to produce a finished part weighing one pound. The newer methods--hot

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[1] The parts may be too complex to be handled by the conventional tools or the sections may be unable to withstand even light machine tool pressures.

[2] Automated electron beam drilling is currently being developed.

pressing and isothermal forging[1]--have reduced this ratio to 2:1. A second reason for the growth of these forming techniques[2] is the number of difficulties (already noted) associated with machining these newer materials.

4. Other Manufacturing Techniques

The aerospace industry has also developed new joining techniques which include automated welding and diffusion bonding. The use of these techniques reduces both the number of complex forgings and the machining which are required to fabricate complex structural parts. Instead, the techniques permit the manufacture of single parts which are then joined to form the finished complex structures.

5. Computer-Aided Design (CAD) and Computer-Aided Manufacturing (CAM)

Some aerospace firms are now adopting manufacturing techniques by which computers directly control the operations of a number of machines. "Dozens of machine tools can now be simultaneously operated and controlled by a single hierarchial computer system...."[3] This procedure increases machine use and therefore the productivity of capital is enhanced. Fewer machines may be required because the same general purpose tool may be programmed to perform different functions on a number of different parts.

In addition, computers aid in design engineering; there has been a considerable reduction in the time required to design

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[1]Both are based on powder metallurgy.

[2]However, there are some additional costs associated with these techniques including the cost and maintenance of dies and the costs associated with the heating and handling problems of the new metallurgical processes.

[3]GAO report, *op.cit.*, p. 19.

and analyze the structure and aerodynamics of a new aircraft.[1] Finally, the same data which are used to create the design may be used to program the machine tool which produces the part.[2]

6. Summary

The increased performance required of the newer military combat aircraft has been partially achieved by using newer materials and more complex structural parts. These factors have in turn required that new production techniques be adopted. The aerospace firms have been responsive and have developed new manufacturing techniques. Some of these techniques were developed by the companies and their suppliers using their own funds, others were funded by the Department of Defense's Manufacturing Technology Program, which is designed to induce innovation in the defense industrial base.[3]

These industrial process innovations have also had impact on the labor force employed by the aerospace industry. This effect will be considered in the next section.

D. LABOR

A number of factors have affected the composition of the work force employed in the aerospace industry. First, the

[1]McDonnell-Douglas estimates that its analyses of the structure and aerodynamics can now be completed in two weeks. Previously, up to six months may have been required to complete the task. *Aviation Week and Space Technology*, October 18, 1976, p. 13.

[2]Therefore, it is conceivable that blue prints or engineering drawings may not be required. However, if the manufacture of the parts must be subcontracted, and if the subcontractor does not have identical CAD/CAM capabilities, then these drawings are required. In some cases this entails a duplication of expenses.

[3]See Department of Defense, *The FY 1981 Department of Defense Program for Research, Development and Acquisition*, Statement by the Honorable William J. Perry, Under Secretary of Defense Research and Engineering delivered to the 96th Congress, Second Session, 1980, pp. I-20-21 and V-12-13.

greater use of numerically controlled machines required that the industry hire more people who can program these machines and substitute capital for production workers. Second, the industry is now required to produce more paper documentation along with the actual physical output,[1] which in turn requires an increase in the number of employees who process these data.

It can be hypothesized that both factors would change the composition of the industry's labor force. There should be a tendency for other employees to increase relative to production workers. The data in Table 9 suggest that the hypothesis is correct. Since 1960, with the exception of the Vietnam War period, there has been a steady decline in the percentage of aircraft industry employees who are classified as production workers.[2]

There is, however, one caveat that should be added. Employment data are not separately available for the civilian and military sections of the standard industrial classification: The Aircraft Industry (SIC 3721). Consequently, the data refer to the entire industry and not to the military portion alone. If it could be shown that the two sectors had different trends, the stated conclusions would have to be modified.

Even among production workers, there has been a compositional change in the work force. The use of titanium and complex parts has increased the amount of labor involved in fabricating airframe components. However, this has simplified

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[1]The point was made by officials within the Department of Defense and by industry sources.

[2]McDonnell-Douglas has indicated that there was a considerable change in the skill composition of the work forces used to manufacture the F-15 as compared with that used to make the F-4. For example, engineers constitute 19 percent of the inplant F-15 work force as compared to 14 percent for the F-4. Moreover, the F-15 figures do not include the large number of employees of the McDonnell automation group who are involved in CAD/CAM tasks for the F-15.

Table 9. EMPLOYMENT IN THE AIRCRAFT INDUSTRY (SIC 3721)

Year	Total Employment (Annual Average, Thousands)	Production Workers (Annual Average, Thousands)	Production Workers at a Percent of Total Employment
1960	337.4	198.4	59
1961	317.1	175.9	55
1962	334.7	175.1	52
1963	335.9	176.9	53
1964	319.2	175.7	55
1965	333.3	184.7	55
1966	417.3	239.8	57
1967	468.2	272.9	58
1968	487.8	280.9	58
1969	456.7	255.1	56
1970	371.2	197.5	53
1971	294.7	149.9	51
1972	287.2	145.1	51
1973	300.5	151.5	50
1974	307.6	154.4	50
1975	292.8	140.9	48
1976	281.1	132.2	47
1977	274.9	126.4	46
1978	304.4	141.4	46

Source: U.S. Department of Labor, Bureau of Labor Statistics, *Employment and Earnings, United States, 1909-78,* Bulletin 1312-11, 1979.

the assembly task and reduced the labor requirements for assembly.[1] The combination of these two factors has increased the proportion of labor required for fabrication relative to that used in assembly. At McDonnell-Douglas, fabrication and assembly of the F-4 accounted for 52 percent and 48 percent of the shop work force, respectively; for the F-15, the comparable figures were 57 percent and 43 percent. This change in the composition of the work force could have an effect on costs since skilled machinists are generally higher paid than are the workers involved in assembly.

E. SUMMARY

This chapter examined the technological changes involved in the manufacture of military combat aircraft. We have noted that all the factors employed in this process were affected, i.e., new materials were introduced, the capital used in the industry was changed, and the composition of the industry's labor work force was affected. The next chapter will employ a case study to show how these technological changes have affected costs of production.

[1] For example, the F-15 airframe requires the use of over 400,000 fasteners; the F-4 used more than 600,000. This is one factor that has reduced man-hours used in assembly by 45 percent. *Aviation Week and Space Technology*, October 29, 1973, p. 48.

Chapter VII

CHANGES IN PRODUCTION COSTS AND TECHNOLOGICAL CHANGE: A CASE STUDY

The previous chapter described the changes in aircraft manufacturing techniques which have occurred over the past two decades. This chapter will examine the impacts that these technological changes have had upon the costs of producing airframes. The analysis (like that of Chapter IV) will show that the cost movements associated with technological change can be divided into two separate factors: the first is associated with reductions in cost attributable to new manufacturing process; the second involves cost increases stemming from the improved qualities or complexity of a newer system.

The particular question to be examined is: How would the production costs of a particular aircraft have changed if the technology utilized to manufacture a successor aircraft has been used to produce the original aircraft? A related question to be considered is: How do the costs of the successor aircraft compare to the costs of the earlier aircraft produced with the newer technology?

These questions are answered by using the F-4 as a case study. The actual costs of producing the F-4 can be obtained from the accounting records of McDonnell-Douglas. The estimated costs of manufacturing the F-4 with a newer production technology were also obtained from McDonnell-Douglas. These estimates were derived on the assumption that some of the F-15 technology would have been used to produce the F-4. Using the F-4 as the original aircraft and the technology used to assemble the F-15 as the newer manufacturing technique is logical. Both aircraft were built by the same company, McDonnell-Douglas, in the same plant, and both aircraft are (were) considered first-line combat aircraft. Moreover, McDonnell-Douglas has been considered one of the leaders in the aerospace industry in adopting new manufacturing techniques.[1]

A. F-4 AIRCRAFT; F-15 TECHNOLOGY

Over a period of twenty years, nearly 5,000 F-4 "Phantom" aircraft were built in a number of distinct models including fighter and reconnaissance versions suitable for either land-based or carrier operation, and sold to the US Air Force and Navy as well as to foreign governments. As the F-4 evolved into its various versions, its weight and configuration changed and the methods for producing it evolved.[2] Thus, if the costs of producing the F-4 with actual technology are to be compared with the estimated costs utilizing an alternative set of techniques, the configuration and lot size has to be specified. For this analysis the lot was the first 155 F-4s delivered to the US Navy and involved the F-4A and F-4B configurations.

McDonnell-Douglas provided the unit cost of producing the 155th F-4 with the then (1962) existing technology. These actual costs were divided into several important categories, direct labor hours utilized in engineering, production and quality control, materials, overhead, etc. The data presented in Table 10, Column 1, show the percentage of the actual unit cost which each major item represented.

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[1] *Aviation Week and Space Technology*, July 28, 1968, pp. 98ff.

[2] For example, parts for the later versions of the F-4 were fabricated by direct computer control of the machine tools as compared to numerical control using tapes.

Table 10. F-4 COSTS: PERCENTAGE OF ACTUAL COSTS ATTRIBUTABLE TO SPECIFIC COST CATEGORIES; RATIO OF ESTIMATED COSTS USING NEW TECHNOLOGY TO ACTUAL COSTS

	Percent of Actual F-4 Cost	Ratio of Estimated (Using New Technology) to Actual Costs
Engineering Direct Labor	3.1	1.000
Tooling Direct Labor	2.7	0.561
Production Direct Labor	18.7	0.772
Quality Assurance Direct Labor	3.0	0.785
Engineering Overhead	2.7	1.000
Manufacturing Overhead	24.5	0.875
Material	16.2	1.127
Subcontract	16.4	0.748
Procurement Expense	3.3	0.900
Other Direct Cost	0.7	1.000
G&A Expense	8.7	0.890
Total Index	100.0	0.875

In order to isolate the effect of these hypothetical changes in production technology upon the estimated costs of the F-4, it is necessary to assume that the configuration of the aircraft would have remained unchanged. Those aspects of the new technology which would have altered the F-4 cannot be considered; new materials cannot be introduced; CAD techniques cannot be used to redesign the plane optimally, for this would have changed the product.

Thus, all aspects of the F-15 manufacturing technology can not be considered in the analysis of the cost changes that would have occurred if the technology had been available and used to produce the F-4. McDonnell-Douglas provided IDA with cost estimates on the assumption that two of the most important aspects of the F-15 technology had been available and used to produce the 155th F-4. These assumptions are (1) many of the structural components of the airframe are built as unitized items which do not require assembly, and (2) the machine tools which are used to fabricate these components are under direct computer control.[1]

B. COMPARISON OF COSTS - OLD AND NEW TECHNOLOGY

1. Total Costs

The theoretical cost estimates of building the 155th F-4 using the newer technology are presented in Table 10, Column 2. For every component, the newer costs are expressed in index number form as a ratio of the original actual costs. Engineering direct labor costs are identical in the two cases, and the corresponding figure is 100 percent. The data show that if the newer technology had been available and used, the total unit cost of the 155th F-4 would have been 12-1/2 percent

[1]There is also an assumption about the slope of the progress curve. It is less steep than the actual slope associated with the F-4's cost. This reflects the F-15 experience.

less. Material costs would have increased relative to the old technology while all other costs would have remained constant or declined relative to the actual outlays.

2. Specific Cost Items

A more detailed comparison of the major cost components would provide additional insights about the effects which technological changes had upon costs. For example, tooling labor costs would have been down over 40 percent if the newer technology had been used, and production direct labor outlays would have been reduced by over 20 percent. These estimates are in accord with our earlier findings (Chapter VI) that newer technology has substituted capital for production workers.

The substitution of capital for labor in the fabrication process has produced even more labor savings in the assembly phase.[1] In a separate set of calculations, McDonnell-Douglas estimated that savings in fabrication manhours would have been about 22 percent while nearly 40 percent less manhours would have been used in the assembly phase.[2] Total unit manhours[3] would have been reduced by about 26 percent.

The introduction of the new technology also would have decreased the work load in the McDonnell plant, thus permitting more items to be fabricated in-house. This explains the decline in subcontracting costs, but there would have been some increase in in-house labor and materials usage. These increases are already included in the assembly and fabrication data.

[1] This is the result of unitized construction of components which reduces assembly time.

[2] Manhours used in the planning operations, however, would have increased.

[3] Total labor *costs* were not reduced as much as manhours because more skilled labor is required for the newer technology, and the wage rate would be higher.

However, the introduction of the new technology would have involved higher material costs, because the unitized components would have been machined from larger forms. This would have entailed higher scrappage losses, and the value of scrap metal is substantially less than that of the purchased material.

Finally it should be noted that the manufacturing overhead *rate* would have increased. This result can be derived from the Table, for manufacturing overhead (relative = 87.6) has declined less than direct production labor costs (relatives =77.3 and 78.5). This increase in overhead rates is attributable to a number of factors. First, the use of the newer technology would have required a larger number of computer specialists to develop the software for controlling the machine tools. These white collar workers would be included in the manufacturing overhead base because they are necessary to produce the aircraft but are not directly employed in the production process. Consequently, the newer technology would also have resulted in a substitution of overhead labor for production workers.[1] Second, the new technology would have required more expensive capital equipment. The increased depreciation would have been recouped via a higher overhead charge.

3. Summary and Caveats

We can conclude that the use of the newer technology would have substantially reduced labor requirements, but that overall costs would not have decreased as significantly. This lesser decline in overall costs would be attributable to the substitution of other factors for labor. Nevertheless, the results lend credence to the hypothesis that over time new

[1]With a reduction in production labor hours, even a fixed amount of overhead labor would have required an increase in the overhead *rate*, for there would be fewer hours over which to spread the fixed costs.

technological processes reduce the costs of manufacturing a particular weapon system.

It should be noted that this cost comparison was made for a buy of 155 aircraft. Since the progress curve slopes for the two technologies would not be identical, similar results might not apply at different quantities of cumulative output.[1] In particular, it is possible to speculate that the new technology's labor savings might be smaller for larger buys since the progress curve for the F-4 is steeper than it is for the F-15.[2]

C. F-15 AIRCRAFT; F-15 TECHNOLOGY

The discussion in Chapter IV indicated that it was necessary to divide the analysis of simultaneous product and process changes into its component parts, i.e., (1) an old product produced with old technology, (2) the identical old product made with new technology, and (3) a new item manufactured with the identical newer techniques. We have been able to accomplish part of this task by comparing the costs of an F-4 made with the original techniques with the costs that might have occurred if *some* of the F-15 technology had been utilized.

Unfortunately, we are not able to completely analyze the final set of costs, i.e., those of an F-4 made with the *complete* F-15 technology and those of the F-15 using its own existing methods. We have already indicated that it was not possible to determine how much an F-4 would have cost if the entire set of F-15 production techniques had been used, for this would

[1]The results might also be affected by the rate of output, i.e., the number of aircraft per month.

[2]The proper curve might be less steep for the F-15 because the production process is more mechanized and less learning could occur.

have entailed design changes, and the nature of the F-4 would have been altered.

There are some additional data which shed some light about the relationship between the production costs of (1) the F-4 as actually made, (2) the F-4 as it would have been made using some of the F-15 technology, and (3) the F-15 as actually produced. McDonnell-Douglas indicated that, for the 155th aircraft, the *per pound unit manhour production costs* of the F-15 were slightly lower than those of the F-4 as actually produced.[1] The early F-15 weighed more than did the early F-4. Consequently, after adjusting for this weight difference, the number of production manhours per plane would be approximately equal for the two planes.

The analysis presented earlier in this chapter showed that there would have been a 26 percent savings in production manhours if the F-4 had been manufactured using some of the newer techniques. It is therefore possible to infer that there would have been a comparable increase in production manhours for the F-15 compared to the F-4 made with the newer technology.

These results are illustrated[2] in Figure 9 which shows the estimated unit production costs (index number form) of the first 155 units of (1) the F-4 as actually built, (2) the F-4 as hypothetically constructed using some of the F-15 technology and (3) the F-15 as actually built. The graph shows the actual F-4 and F-15 having nearly identical costs of 100 with hypothetical costs of 74 for the F-4 made with the newer technology. The results show that the new technology

[1] We are not certain whether subcontracted production work is included in these data.

[2] The graph is similar to the graph illustrating the theory for disentangling the two types of technological change. That graph appeared in Figure 1 in Chapter IV.

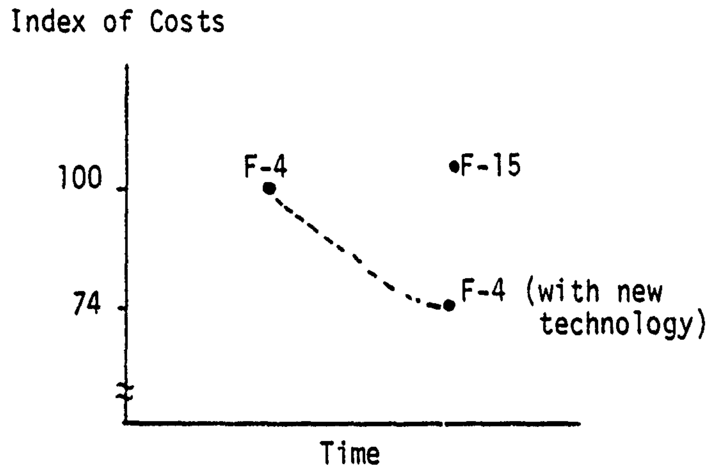

Figure 9. UNIT PRODUCTION MANHOURS OF THE 155TH F-4, F-15, AND AN F-4 BUILT WITH F-15 TECHNOLOGY

reduced costs, and that the increased costs for the F-15 must be attributed to factors resulting from higher performance requirements.

More titanium is used to make the F-15 than is contained in the F-4.[1] Composites have also been introduced in the F-15. Both composites and titanium cost more per pound than does aluminum. It is thus possible to infer that material costs of the F-15 would have risen relative to those of the F-4 made with the newer methods.

We do not have hard data for the remaining cost categories of the F-15, nor do the industry trade publications provide much additional guidance.[2] There is some suggestion that more wind tunnel hours were used for the F-15 than for the F-4, but the other categories of cost have not been analyzed thoroughly.

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[1]We previously indicated that 34 percent of the airframe weight of the F-15 was titanium; the comparable figure for the F-4 was 9 percent.

[2]*Aviation Week and Space Technology* provides some information about F-15 program costs. See the issues of April 9, 1973, pp. 14-15, October 29, 1973, pp. 47-52; July 15, 1974, pp. 111-116; and August 2, 1976, pp. 38-41.

Although incomplete, the data are sufficiently suggestive to support the hypothesis that the new aircraft cost more than the older aircraft using the same technology. This finding is in accord with previous studies which show that new weapon systems experience cost increases over the system being replaced, with the requirements for improved performance accounting for a significant portion of the increase.[1]

D. SUMMARY

The two basic findings of this chapter are obtained from a case study of the F-4 and F-15 technologies. The results indicate (1) new production technologies reduce the cost of manufacturing a particular weapon system, and (2) new weapon systems experience cost increases relative to the system being replaced.

These results are in accord with the hypotheses advanced in Chapter IV, namely, that it is expected that process improvements will reduce costs while the requirements for improved performance will increase costs. The implications that these results have upon the procedures used to estimate the costs of weapon systems will be presented in the next chapter.

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[1] *Aviation Week and Space Technology*, August 28, 1972, p. 18; November 19, 1973; p. 61. A similar point with respect to commercial aircraft was made by Almarin Phillips, "Technology and Market Structure, A Study of the Aircraft Industry," Lexington Books, Lexington, MA, 1971.

Chapter VIII

CONCLUSIONS AND SUMMARY RECOMMENDATIONS

It is now necessary to place the results of the previous chapters in perspective and to analyze the implications of the findings for the existing cost estimating methodology.

A. CONCLUSIONS

Our results clearly show that over the past two decades two types of technological change have occurred in the airframe industry (similar findings for airborne fire control radar are presented in Appendix D):

- The performance requirements of aircraft have increased; aircraft have become more complex; new systems have been incorporated into the aircraft; new materials are utilized to construct the airframe components.
- These technological changes which have affected the characteristics of aircraft are also associated with technological developments which have transformed the methods of manufacturing these combat aircraft.
- These technological changes help to explain some of the biases which were observed in the cost estimates obtained from a preferred airframe CER (Chapter II).
- The overestimates of the number of manhours required for tooling can be explained by the substitution of capital for labor in this activity.
- Similarly, some of the underestimates in materials costs might result from the use of more expensive materials and the use of unitized components which entail more scrappage.

- *In the presence of technological change, the preferred airframe CER may no longer be valid.* For example, the CER for aircraft indicates that costs are positively related to the weight and maximum speed of the aircraft. However, the weight of modern aircraft is reduced only because more expensive materials have been substituted for the older, cheaper but heavier materials. Thus, with everything else held constant, weight and cost are negatively related--not positively as is implied by the CER.
- This finding leads to a more specific conclusion. *A CER based on specific characteristics of older weapon systems may be used only if the characteristics of new systems do not require new production technologies,* i.e., if the relationship between system characteristics and the production function remains unchanged and stable.

B. RECOMMENDATIONS

Since there have been structural changes in the aerospace industry, we recommend that modifications be made in the cost estimating methodology for airframes to reflect those technological changes.

- If the qualities of characteristics of newer systems require a new production technology, this factor must be incorporated into CERs.
- The characteristics that are included in a CER must in fact be the factors that drive costs. For example, the complexity of the system or the requirement that a titanium-based technology must be used might be factors that drive costs.
- It might be possible to modify existing CERs by including an index of complexity, even though some previous studies have failed to find such a variable significant. While holding other system characteristics constant, such an index would shift a CER upward or downward, depending on the complexity of the product.
- An index of complexity would involve both the system characteristics and/or performance and the manufacturing technology required to produce the system. Such an index might be constructed using the Delphi approach.

- An additional variable that might be included in existing airframe CERs is the percentage of newer materials that are embodied in the airframe.
- Existing airframe CERs focus on manhours and materials costs. Given the recent substitution of company-owned capital equipment for labor, some extra attention should be focused on analyzing the capital charges in the overhead rate.

Appendix A

EMBODIED TECHNOLOGICAL CHANGE

EMBODIED TECHNOLOGICAL CHANGE

Embodied technological change may either be composition neutral or it may change the substitution relationship of the production function. In the former case, the production function is represented by equation (10) of Chapter III. More generally, however, we expect that new technological change will not be composition neutral, but rather that it will affect different factors differentially. We may produce this in the most general fashion by altering equation (8) of Chapter III:

$$1 = Be^{rX_K^{\theta_K}}K^c{}_L^{\theta_L}L^b{}_M^{\theta_M}M^k \quad . \qquad \text{(A-1)}$$

Thus, a new robotized assembly machine may be expected to alter the substitution relations among all inputs and, hence, given fixed input prices, alter the minimum-cost input composition.

We shall distinguish this discontinuous type of technological change from the "learning" type by the term "embodied," because it is accompanied by changes in the types of capital, labor, and materials used in the production of the F-x. Most generally it is associated with the introduction of new capital. For example, let us illustrate the realistic implications of embodied technological change with the assumption that, at the X_1^{th} cumulative unit, the technology changes from

$$1 = Be^{rX}K^{c}L^{b}M^{k}\ , \quad X \leq X_1 \qquad \text{(A-2)}$$

$$1 = B e^{rX}\,{}_{K}^{\theta}K^{c}\,{}_{L}^{\theta}L^{b}\,{}_{M}^{\theta}M^{k}\ , \quad X > X_1 \leq \bar{X}\ , \qquad \text{(A-3)}$$

where $\bar{X}$ is the last unit of F-x produced.[1]

Suppose, however, that it is not possible to institute the new technology completely at the time of the X_1th unit's production; rather, it is instituted incrementally as more old capital is replaced with new. Under the old regime the lowest-cost capital input was K_1, and under the new conditions this changes to K_2. At the X_1th unit K_a units of new vintage capital are installed, where $K_a < K_2$. Then we may approximate the realistic technology as

$$1 = \left(1-\lambda\right)\left(B_1 e^{rX}K_1^{c}L_1^{b}M_1^{k}\right) + \lambda\left(B_2 e^{rX}K_2^{c}L_2^{b}M_2^{k}\right)\ , \qquad \text{(A-4)}$$

where $\lambda = K_a/K_2$, so that λ is the proportion of new vintage capital in place.

[1]Note that we assume the learning rate r remains constant. In (A-3) however, if a substantial re-learning process is necessary, then X in (A-3) should be changed to $(X-X_1)$. Realistically, of course, r may well change.

Appendix B

MINIMIZATION-OF-COST FACTOR MIX DERIVATION LEARNING CURVES

MINIMIZATION-OF-COST FACTOR MIX DERIVATION LEARNING CURVES

A. COST MINIMIZATION

The problem is to

$$\text{Min } C = K \cdot P_K + L \cdot P_L + M \cdot P_M \tag{B-1}$$

subject to

$$K^c L^b M^k = B^{-1} e^{-rX} . \tag{B-2}$$

For convenience, define

$$S \equiv B^{-1} e^{-rX} . \tag{B-3}$$

Then, the Lagrangean form is

$$\text{Min } Z = K \cdot P_K + L \cdot P_L + M \cdot P_M - \lambda(K^c L^b M^k - S) , \tag{B-4}$$

and setting the gradient vector equal to zero yields the first-order conditions:

$$.1 \quad \frac{\partial Z}{\partial K} = P_K - \lambda c K^{c-1} L^b M^k = 0 . \tag{B-5}$$

$$.2 \quad \frac{\partial Z}{\partial L} = P_L - \lambda b K^c L^{b-1} M^k = 0$$

$$.3 \quad \frac{\partial Z}{\partial M} = P_M - \lambda k K^c L^b M^{k-1} = 0$$

$$.4 \quad \frac{\partial Z}{\partial \lambda} = K^c L^b M^k - S = 0$$

If $K^c L^b M^k$ is concave in K, L and M, second-order minimum conditions will be met. This production relation will be met if and only if $0 \leq c, b, K \leq 1$; which we assume. By multiplying (B-5.1), (B-5.2) and (B-5.3) by $K^c L^b M^k / S$, we obtain

$$.1 \quad P_K - \lambda c S K^{-1} = 0 \qquad \text{(B-6)}$$

$$.2 \quad P_L - \lambda b S L^{-1} = 0$$

$$.3 \quad P_M - \lambda k S M^{-1} = 0 \; .$$

Hence,

$$.1 \quad K^0 = \frac{C \lambda S}{P_K}$$

$$.2 \quad L^0 = \frac{b \lambda S}{P_L}$$

$$.3 \quad M^0 = \frac{k \lambda S}{P_M} \; ,$$

and substituting in (B-1) yields

$$C = \lambda S(c+b+k) \qquad \text{(B-8)}$$

$$= \lambda(c+b+k) B^{-1} e^{-rX} \; .$$

Let

$$U \equiv \lambda(c+b+k) B^{-1} \; .$$

Then the minimal cost function is

$$C = U_e^{-rX} \; . \qquad \text{(B-10)}$$

If we allow X to vary (holding product characteristics and input prices constant) the incremental cost function follows (B-10). Hence, the "true" form of the learning curve under these conditions is this exponential function--a semilog function rather than the usual logarithmic formulation:

$$C = AX^{a} . \qquad \text{(B-11)}$$

B. DISEMBODIED TECHNICAL CHANGE

We may now relate the learning curve to the production function with disembodied change

$$1 = Be^{rX}K^{c}L^{b}M^{k} , \qquad \text{(B-12)}$$

from which we obtain

$$e^{rX} = (BK^{c}L^{b}M^{k})^{-1} . \qquad \text{(B-13)}$$

The power series expansion of e^{rX} is

$$e^{rX} = 1+rX+\frac{(rX)^2}{2!} + \frac{(rX)^3}{3!} + \ldots + \frac{(rX)^n}{n!} + \ldots \quad . \qquad \text{(B-14)}$$

For rX sufficiently small we may approximate e^{rX} by the linear portion of (B-14), so that (B-13) may be approximated by

$$1 + rX = (BK^{c}L^{b}M^{k})^{-1} . \qquad \text{(B-15)}$$

Then

$$X = r^{-1}(BK^{c}L^{b}M^{k})^{-1}{}_{-1} . \qquad \text{(B-16)}$$

By substituting into (B-11) we obtain

$$C_X = \frac{A}{r^a}\left[(BK^cL^bM^k)^{-1} - 1\right]^a \tag{B-17}$$

where

$$K^cL^bM^k = B^{-1}e^{-rX} \quad . \tag{B-18}$$

C. THE LEARNING CURVE WITH EMBODIED TECHNOLOGICAL CHANGE

We incorporate embodied technological change into the learning curve analyses by shifting to lower learning curves. For example, for composition neutral technological change, we suppose that new machinery purchases change the F-x production function from (B-12) to (B-19):

$$1 = \theta Be^{rX}K^cL^bM^k \quad . \tag{B-19}$$

The learning curve then changes from

$$C_1 = \frac{A}{r^a}\left[(BK_1^cL_1^bM_1^k)^{-1} - 1\right]^a, \quad K_1^cL_1^bM_1^k = B^{-1}e^{-rX} \tag{B-20}$$

to

$$C_2 = \frac{A}{r^a}\left[(BK_2^cL_2^bM_2^k)^{-1} - 1\right]^a, \quad K_2^cL_2^bM_2^k = \theta^{-1}B^{-1}e^{-rX} \quad . \tag{B-21}$$

Hence

$$\frac{C_2}{C_1} = \left(\frac{(\theta BK_2^cL_2^bM_2^k)^{-1} - 1}{(BK_1^cL_1^bM_1^k)^{-1} - 1}\right)^a = \left(\frac{1-\theta BK_2^cL_2^bM_2^k}{\theta(1-BK_1^cL_1^bM_1^k)}\right)^a$$

$$= \left(\frac{1-e^{-rX}}{\theta(1-e^{-rX})}\right)^a = \left(\frac{1}{\theta}\right)^a \quad . \tag{B-22}$$

Therefore, if embodied technological change is composition neutral, the new learning curve will shift downward and be parallel to the old when graphed on a double logarithmic grid.

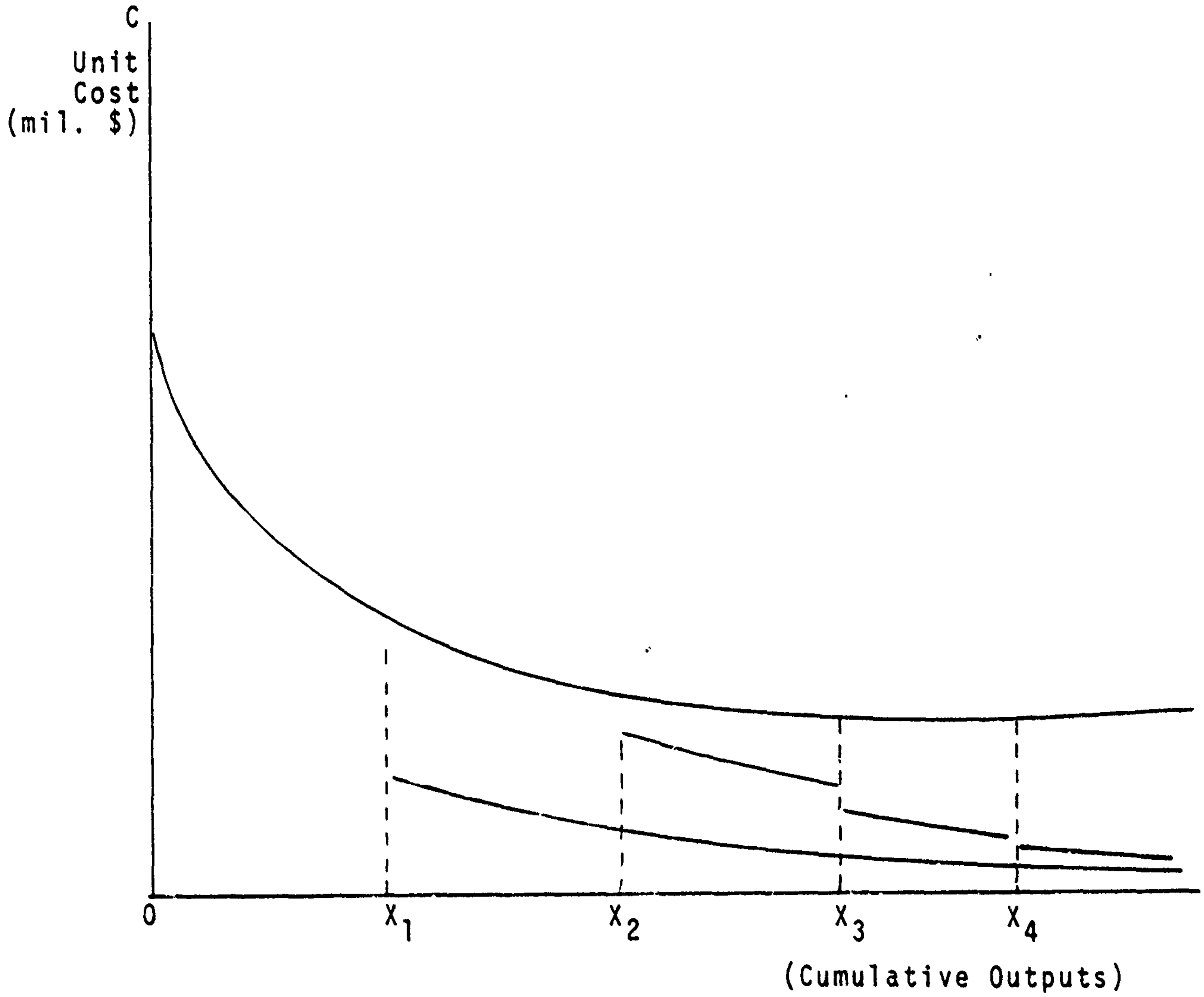

Figure B1. LEARNING CURVES AND EMBODIED TECHNOLOGICAL CHANGE

We shall approach reality more closely if we recognize that the new technology will not be introduced abruptly, but will generally be changed at discrete intervals as innovatory capital and/or materials are introduced. The actual cost of the ith F-x, therefore, will now be a function of the "vintages" of the capital installed.

Assume--realistically--that to manufacture the F-x under a given embodied technology requires a fixed amount of capital $\bar{K}_1$ and that a new embodied technology changes this fixed quantity to $\bar{K}_2$. Moreover, factor savings induced by learning results in labor and/or materials savings. Suppose that at output unit X_1 the new technology becomes known, so that were adaptation instantaneous (and learning continuous), the firm would shift to learning curve C_2. However, not until unit output X_2 does the portion $\Delta K_{2,2}$ become available. Let $\alpha_2 = \Delta K_2 / \bar{K}_2$, and we may approximate the hybrid cost curve resulting as:

$$C' = \alpha_2 \cdot C_2 + (1-\alpha_2)C_1 , \qquad \text{(B-23)}$$

as shown on Figure B1. At X_2, $\Delta K_{2,3}$ is installed, so that $\alpha_3 = (\Delta K_{2,2} + \Delta K_{2,3})/\bar{K}_2$, and

$$C'' = \alpha_3 \cdot C_2 + (1-\alpha_3)C_1 . \qquad \text{(B-24)}$$

At X_4 another installation occurs, C"' is attained, and so forth until C_2 is reached (if it is) when all capital is new vintage.

If a progress curve is fitted econometrically to the learning curve specification, without recognition of these vintage capital changes, actual observations obtained will be points on the various curves C_1, C', C", C"', and C_2. The curve will then represent a hybrid, confusing the effects of both embodied and disembodied technology.[1]

[1]Hence, Oi's conjecture may be explained in just these terms: "The instability and limited reliability of the progress functions suggest that if learning is the underlying force it does not operate in a smoothly predictable fashion." Walter Oi. "The Neoclassical Foundations...," *loc.cit.*

From our analyses, even were r to remain constant along the hybrid learning curves, the observed progress curves would have these discontinuities. Oi's explanation is that the ability of producers to substitute inputs and outputs over time in a Hicksion production function formulation may lead to economies which are confused with learning.[1] The explanation does not seem plausible to us in terms of the defense industry and its scheduled production flows.

Including embodied technological change of the factor composition affecting type given by

$$1 = Be^{rX}\,{}_K^{\theta}K^{c}\,{}_L^{\theta}L^{b}\,{}_M^{\theta}M^{k} \tag{B-25}$$

offers no conceptual problems different from those discussed above. The relevant learning curve is written:

$$C_x = \frac{A}{r^a}\left[B\left({}_K^{\theta}K^{c}\right)\left({}_L^{\theta}L^{b}\right)\left({}_M^{\theta}M^{k}\right)^{-1} -1 \right]^a \tag{B-26}$$

where

$$\left({}_K^{\theta}k^{c}\right)\left({}_L^{\theta}L^{b}\right)\left({}_M^{\theta}M^{k}\right) = B^{-1}e^{-rX} . \tag{B-27}$$

Technology changes will now affect factor input compositions so that, even when r remains constant between technologies, the implied learning curves will not be (logarithmically) parallel.

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[1]Walter Oi, *loc. cit.*

Appendix C

PRODUCT QUALITIES, PRODUCTION FUNCTIONS, AND LEARNING CURVES

PRODUCT QUALITIES, PRODUCTION FUNCTIONS, AND LEARNING CURVES

This Appendix demonstrates how product qualities can be incorporated into the production function and then considers the relationship between learning curves and CERs.

A. FACTOR COMPOSITION NEUTRAL QUALITY CHANGES

Let us define a set of cost-relevant product characteristics, $Q_i = 1, 2, \ldots, n$. For example, let $n = 2$ for aircraft and suppose Q_1 to be maximum speed and Q_2 to be range. We assume that our problem is to estimate a new learning curve for F-x whose speed and range qualities are changed, but which can be produced with essentially the same disembodied and embodied technology.

The simplest manner of accommodating the implied input-output relationships is to assume that such changes will have no impact upon the minimum-cost factor proportions, and to estimate such a production function in the form

$$1 = B^{\left(\delta_1 Q_1 + \delta_2 Q_2\right)} e^{rX} K^{c} L^{b} M^{k} \quad . \tag{C-1}$$

Then

$$C_X = \frac{A}{r^a}\left[\left(B^{\delta_1 Q_1 + \delta_2 Q_2} K^{c} L^{b} M^{k}\right)^{-1}\right]^{a} \tag{C-2}$$

$$K^{c} L^{b} M^{k} = B^{-(\delta_1 Q_1 + \delta_2 Q_2)} e^{-rX} \quad . \tag{C-3}$$

Consider X = 100. For (C-3) define

$$T_{100} = K^c L^b M^k \text{ meeting (C-3) when } X = 100.$$

Then (C-2) simplifies to

$$C_{100} = \frac{A}{r^a}\left[T_{100}\left(B^{\delta_1 Q_1 + \delta_2 Q_2}\right)^{-1} - 1\right]^a . \qquad \text{(C-4)}$$

Suppose the current qualities of fighter aircraft are $[Q_1, Q_2]_1$ and let $B_1^\delta = B^{\delta_1 Q_{11} + \delta_2 Q_{21}}$.

From (C-4)

$$C_{100} = \frac{A}{r^a}\left(\frac{1 - T_{100} B_1^\delta}{T_{100} B^{\delta}_1}\right)^a , \qquad \text{(C-5)}$$

where is the X = 100 point on the current learning curve.

Suppose that a different speed-range quality complex, $[Q_1, Q_2]_2$, were contemplated for the F-x, producible with essentially the same technology. Then, for X = 100, we define

$$C'_{100} = \frac{A'}{r^a}\left(\frac{1 - T'_{100} B_2^\delta}{T'_{100} \; B_2^\delta}\right)^a \qquad \text{(C-6)}$$

where $B_2^\delta = B^{\delta_1 Q_{12} + \delta_2 Q_{22}}$ and

$$T'_{100} \equiv K^c L^b M^k = B^{-(\delta_1 Q_{12} + \delta_2 Q_{22})} e^{-rX} , \; X = 100.^{1} \qquad \text{(C-7)}$$

In Appendix A it was shown that, for given input prices, the input proportions for both types of aircraft will be the same.

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[1]We assume a is unchanged because r is unchanged. This need not hold rigidly.

It follows, therefore, that C_x' will be different from C_x by the multiplicative factor A'/A.

$$\frac{C'_{100}}{C_{100}} = \frac{\frac{A'}{r^a}\,(e^{100r}-1)^a}{\frac{A}{r^a}\,(e^{100r}-1)^a} = \frac{A'}{A} \tag{C-8}$$

where X = 100 is chosen arbitrarily. Therefore, knowing C'_{100}--or any other single point on the new learning curve--permits us to obtain the new learning curve

$$C'_x = \left(\frac{C'_{100} \times A}{C_{100}}\right)X^a = A'X^a \ . \tag{C-9}$$

On a log-log grid, C'_x charts as a straight line parallel to C_x, and in this sense we may speak of the new learning curve as a parallel shift of the old *when* (1) *product qualities change in a factor composition neutral manner;* (2) *technology remains constant; and* (3) *the rate of learning (disembodied technological change) remains constant.*

We have, then, derived a CER under these simplest of conditions, for

$$C'_{100} = \frac{A'}{r^a}\left[(T'_{100}B^{\delta_1 Q_{12}+\delta_2 Q_{22}})^{-1} -1\right]^a \tag{C-10}$$

given (C-7) relates qualities Q_{12} and Q_{22} to the incremental costs of the 100th unit of output, which we have seen to be a point on the new learning curves. Its form suggests that the usual assumption about the form of the CER

$$C'_{100} = DQ^m_{12}Q^n_{22} \tag{C-11}$$

is not an accurate specification even under these simplest assumptions.

However, in one important respect (C-11) conforms to the implications of our analyses *for this simplest case.* We have seen that in our analyses

$$\frac{C'_{100}}{C_{100}} = \frac{A'}{A} = \Omega \ . \qquad \text{(C-12)}$$

From (C-11)

$$\frac{C'_{100}}{C_{100}} = \left(\frac{Q^m_{12}Q^n_{22}}{Q^m_{11}Q^n_{21}}\right) = \psi \ . \qquad \text{(C-13)}$$

Hence, the conventional formulation in (C-11) implies a parallel shift in the curves (in logarithmic form), just as (C-12) projects. Hence if $\psi=\Omega$--a result that is by no means guaranteed--the CER and learning curve would yield similar results.

B. FACTOR-COMPOSITION NON-NEUTRAL QUALITY CHANGES

If quality changes are not neutral in their impacts upon factor composition we may represent the relationship via the production function

$$1 = Be^{rX}\left(K^{\alpha_1 Q_1 + \alpha_2 Q_2}\right)\left(L^{\beta_1 Q_1 + \beta_2 Q_2}\right)\left(M^{\gamma_1 Q_1 + \gamma_2 Q_2}\right) , \qquad \text{(C-14)}$$

which for a given $[Q_1, Q_2]$ complex for the F-x we may abbreviate to

$$1 = Be^{rX}K^{\alpha}L^{\beta}M^{\gamma} \qquad \text{(C-15)}$$

where α, β, and γ are the indicated linear functions of Q_1 and Q_2.

Then, the learning curve is

$$C_x = \frac{\tilde{A}}{r^a}\left[(BK^{\alpha}L^{\beta}M^{\gamma})^{-1} - 1\right]^a \qquad \text{(C-16)}$$

with

$$K^{\alpha}L^{\beta}M^{\gamma} = B^{-1}e^{-rX} \; . \qquad \text{(C-17)}$$

Suppose, once more, we contemplate a different speed-range complex, $[Q_1,Q_2]_2$, for the F-x. Then *if* r (and a) remain constant, once more the new learning curve will be a parallel shift (logarithmically) of the first. This must be because, as long as a is held constant in the learning curve $C_x = \tilde{A}X^a$, all changes in cost that result from a change in factor proportions must impact[1] $\tilde{A}$ and $\tilde{A}'$ only. Hence, similar to our analyses in (C-8)

$$\frac{C'_{100}}{C_{100}} = \frac{\frac{\tilde{A}'}{r^a}\left[(BK^{\alpha'}L^{\beta'}M^{\gamma'})^{-1} - 1\right]^a}{\frac{\tilde{A}}{r^a}\left[(BK^{\alpha}L^{\beta}M^{\gamma})^{-1} - 1\right]^a} = \frac{\tilde{A}'(e^{100r}-1)^a}{\tilde{A}\,(e^{100r}-1)^a} = \frac{\tilde{A}'}{\tilde{A}} \; . \qquad \text{(C-18)}$$

Our conclusion about the consistency of the conventional CER's specification with this structural characteristic is the same as that derived from (C-13).

But it is not acceptable to assume that r (and a) remain constant as factor proportions change. Presumably, input mixes with relatively more labor have more potential for higher learning rates r. If quality changes imply input mix changes, the whole logic of disembodied technological change (i.e., learning) argues that r and a must change.

[1]However $\tilde{A}'$ and A' probably would not be identical if the technology changed as a result of non-neutral product quality changes.

Therefore (C-18) must now be written

$$\frac{C'_{100}}{C_{100}} = \frac{\frac{A'}{r'^{a'}} (e^{100r'}-1)^{a'}}{\frac{A}{r^a} (e^{100r}-1)^a} \neq \frac{A'}{A} \quad . \qquad \text{(C-19)}$$

Simplifying by power series and cancelling terms, the relation (C-19) becomes

$$\frac{C'_{100}}{C_{100}} = \frac{\tilde{A}'}{\tilde{A}} (100)^{a'-a} \qquad \text{(C-20A)}$$

and more generally

$$\frac{C'_x}{C_x} = \frac{\tilde{A}'}{\tilde{A}} (X^{a'-a}) \quad . \qquad \text{(C-20B)}$$

No longer, therefore, will C' be a (logarithmically) parallel displacement of C_x, nor will (C-12) be consistent with (C-20). If the conventional CER is used to obtain a point and the old learning curve is plotted through it, gross differences will result from the true relationship.

C. PRODUCT QUALITIES AND EMBODIED TECHNOLOGICAL CHANGE

We have one last complication to consider before concluding our theoretical analysis linking production functions to CERs via the learning curve. In our consideration of product quality variations, we have included disembodied technological change but we have excluded embodied technological change. That is, we have conceived of product changes in important dimensions of the F-x under the assumption that no important modifications in the characteristics of capital, labor, or materials are required, and that no changes occur in the possible input mixes to produce an F-x.

This is, of course, unrealistic. Ordinarily, product changes are effected by installation of new machinery, the employment of new labor skills, and the use of new materials. New substitution relationships may well exist among these inputs under the new technology.

Product change must, therefore, be coupled with implied embodied technology change. To do so we shall treat four different types of such interactions in sequence. The combinations relate to whether the product changes and the technology are factor-composition neutral or not. Fortunately, we shall be able to draw copiously on the previous section's analyses and therefore be rather brief in our consideration of each case.

1. Factor-Composition Neutral Quality and Embodied Technological Change

When neither quality changes nor the implied new technology affect the composition of inputs for an F-x, we may represent the new production function as

$$1 = \theta\, B^{\delta_1 Q_1 + \delta_2 Q_2}\, e^{rX} K^c L^b M^k \,. \qquad \text{(C-21)}$$

The learning curve is then

$$C_x = \left[\frac{A}{r^a} \left(\theta \left(B^{\delta_1 Q_1 + \delta_2 Q_2}\right) K^c L^b M^k\right)^{-1} -1\right]^a , \qquad \text{(C-22)}$$

in straightforward application of our methodology. If r (and a) remain constant under such transformations, we obtain a new CER with the form

$$C'_{100} = \frac{A'}{r^a} \left[\left(\theta \left(B^{\delta_1 Q_{12} + \delta_2 Q_{22}}\right) K^c L^b M^k\right)^{-1} -1\right]^a , \qquad \text{(C-23)}$$

which differs considerably from the conventional form

$$C'_{100} = DQ^{m}_{12}Q^{n}_{22} \; . \qquad \text{(C-24)}$$

However, following our prior reasoning and the derivation in (C-8) there, we conclude that a (logarithmically) parallel shift of the learning curves would occur, as (C-11) and (C-24) used straightforwardly would project.

However, we reject the possibility that r (and a) could remain constant even when product/technological changes of this simplest form occur. It is necessary to rewrite (C-23) as

$$C'_{100} = \frac{A'}{r'^{a'}} \left[\left(\theta \left(B^{\delta_1 Q_{12} + \delta_2 Q_{22}} \right) K^{c} L^{b} M^{k} \right)^{-1} - 1 \right]^{a'} , \qquad \text{(C-25)}$$

which leads to the nonparallel shift in learning curves discussed above.

2. Factor-Composition Neutral Quality Change, Non-Neutral Technological Change

The production function under these conditions is written

$$1 = \left(B^{\delta_1 Q_1 + \delta_2 Q_2} \right) e^{rX} \left(K^{\theta_K c} \right) \left(L^{\theta_L b} \right) \left(M^{\theta_M k} \right) , \qquad \text{(C-26)}$$

which yields the learning curve

$$C_X = \frac{A}{r^a} \left[\left(B^{\delta_1 Q_1 + \delta_2 Q_2} \right) \left(K^{\theta_K c} \right) \left(L^{\theta_L b} \right) \left(M^{\theta_M k} \right)^{-1} - 1 \right]^{a} , \qquad \text{(C-27)}$$

$$\left(K^{\theta_K c} \right) \left(L^{\theta_L b} \right) \left(M^{\theta_M k} \right) = \left(B^{-\delta_1 Q_1 - \delta_2 Q_2} \right) e^{-rX} \; . \qquad \text{(C-28)}$$

Once more, for any two quality sets and implied factor mixes, r (and a) will be different, which means that old and new learning curves will have different slopes.

3. Factor-Composition Non-Neutral Quality Change, Neutral Technological Change

In these circumstances and by using our (now familiar) techniques, the learning curve may be written

$$C_x = \frac{A}{r^a}\left[\left(\theta Be^{rx}\right)\left(K^{\alpha_1 Q_1+\alpha_2 Q_2}\right)\left(L^{\beta_1 Q_1+\beta_2 Q_2}\right)\left(M^{\gamma_1 Q_1+\gamma_2 Q_2}\right)^{-1} -1\right]^a \tag{C-29}$$

where

$$\left(K^{\alpha_1 Q_1+\alpha_2 Q_2}\right)\left(L^{\beta_1 Q_1+\beta_2 Q_2}\right)\left(M^{\gamma_1 Q_1+\gamma_2 Q_2}\right) = \theta^{-1}B^{-1}e^{-rX} \; . \tag{C-30}$$

In general, r (and a) will change between quality mixes.

4. Factor-Composition Non-Neutral Quality and Technological Change

In this most likely case, the learning curve will be

$$C_x = \frac{A}{r^a}\left[\left(Be^{rX}\right)\left(K^{\alpha_1 Q_1+\alpha_2 Q_2+\theta_K c}\right)\left(L^{\alpha_1 Q_1+_2 Q_2+\theta_L b}\right)\left(M^{1 Q_1+2 Q_2+\theta_M k}\right)^{-1} -1\right]^a \tag{C-31}$$

subject to

$$\left(K^{\alpha_1 Q_1+\alpha_2 Q_2+\theta_K c}\right)\left(L^{\beta_1 Q_1+\beta_2 Q_2+\theta_L b}\right)\left(M^{\gamma_1 Q_1+\gamma_2 Q_2+\theta_M k}\right) = B^{-1}e^{-rX} \; . \tag{C-32}$$

Again, we expect r (and a) to change with the joint variations in qualities and technologies.

Appendix D

TECHNOLOGICAL CHANGE IN AIRBORNE FIRE CONTROL RADARS

TECHNOLOGICAL CHANGE IN AIRBORNE FIRE CONTROL RADARS

The main body of this paper focused on technological changes which have occurred in the airframe segment of the defense industry. We will demonstrate in this Appendix that it is possible to apply the same methodology to a segment of the avionics industry--airborne fire control radars. These radars were chosen for analysis because they were considered representative of the entire avionics industry. We will examine changes in manufacturing technology which have reduced costs. An analysis of changes in performance is followed by an estimate of the reduction of costs attributable to manufacturing efficiency.

A. MANUFACTURING TECHNOLOGICAL CHANGE

Within the 1960 to 1980 period many technical innovations in manufacturing airborne fire control radar evolved. One of the earliest involved *preforming component leads*, so enabling assembly workers to more rapidly insert the components into printed circuit boards.[1] This resulted in major savings in assembly labor. A further step in automation came with the introduction of *automatic component insertion* techniques. Special purpose machines were developed to drop components into their proper places on the printed circuit boards; a further increase in productivity resulted when *multi-layered printed circuit boards* came into use to reduce the amount of

[1] Although printed circuit boards were new to the industry in 1960, they were beginning to be used extensively.

wiring required in using several boards. Subsequently, like the airframe segment of the defense industry, *numerically controlled* machine tools came into use to reduce the cost of metal fabrication. The flexibility of using these tools permitted them to be used in the insertion of components onto boards. The application of computers in this industry also permitted the introduction of *automated testing*. At the component level, automated testing not only reduced the labor involved in the testing itself but also permitted increased testing and reduced malfunctions of assembled circuits.[1]

A subsequent manufacturing development was the introduction of *thin/thick film hybrid circuits*. In these, some of the resistors and capacitors that had previously been bought as discrete components in printed circuit board technology were fabricated in place. Etching was used to remove metal and various types of depositions were used to add metal when required. Components which were too complex to fabricate in this manner were purchased without external protective jackets to minimize both the cost and the size of the circuit. After assembly on a glass or strate resembling a miniature printed circuit board, the whole circuit was sealed.

A new technique for reducing the cost (and loss of reliability) associated with making connections between boards was also developed. *Wire-wrapping* was introduced to reduce the amount of soldering required and in some instances to eliminate connectors. Interconnecting cables were typically laid out (in 1960) on a wire by wire basis and laced together after lay-up; the new technique involved embedding a large number of wires in a plastic sheet. The resulting ribbon-like

[1]Automated testing permits more thorough testing at each stage of production and reduces the malfunctions occurring at the next higher level of assembly. Moreover, early fault localization reduces the time and labor requirements involved in the repair of finished systems.

or flat cable effectively reduced the labor in assembling a system. A later development consists of woven cables which provide improvements in assembly.

B. RADAR PERFORMANCE

All the technological changes described above involved improved techniques for manufacturing radars. There were also changes in the performance requirements of radar systems. The 1960 radars had been designed without regard to their susceptibility to jamming and other enemy countermeasures. To overcome this problem, radars were made more powerful to burn through the jamming, as well as more elegant in waveform to help identify the valid signal from among crude facsimiles of the radar's transmission. These electronic counter countermeasures are typically expensive.

Another requirement change of recent years is improved reliability. In response, specifications were tightened, testing was increased, critical circuits were duplicated, and exhaustive failure mode analyses were performed. The improvement in reliability is now reflected in dramatic increases in mean time between failures (and all other indices of reliability). Again, the cost of improved performance has been high.[1]

Several developments over the last few years are only now approaching full fruition. The earliest was the introduction of fully coherent radars. Sometimes referred to as doppler radars, since the coherency of the transmission allows the extraction of the doppler shift produced by target motion, coherent radars were employed in ground-based systems long before they were adapted to airborne usage.[2] However,

[1]However, there is a reduction in operational cost.

[2]For example, Hawk's acquisition and tracking radars are coherent.

the first coherent radars were of the continuous wave type with the result that ground clutter from all ranges within the view of the radar would "pile-up" and compete with the target's return. The solution that permitted the coherent radar to go aloft was the development of pulse doppler radar. In this radar, the range resolution provided by the short pulse reduced the clutter return to whatever small clutter "patch" might be located at the same range and bearing as the target. The introduction of coherent radars and pulse doppler processing gave our airborne fire control radars the "look-down" capability that had been sought for so many years (along with another substantial increment in cost).

The coherent transmitter provided the means for making radars extremely versatile. It became conceptually possible to build a radar that would not only search for and track airborne targets but would also produce a high resolution ground map for aircraft navigation and the surveillance of stationary ground targets, a terrain profile for terrain following/terrain avoidance flight, ground moving target detection, and air to ground weapon fire control. Each of these modes, however, requires different adjustments of controls and, more importantly, a different form of signal processing. The versatility provided would overwhelm all but the most accomplished and experienced full-time radar operators if radar control and processing were performed in the manner of the early 1960s.

The obvious solution was to use *digital logic and control* to relieve the pilot of the burden of becoming an expert radar operator. The early digital signal processors were hard wired, but more recent radars use a *programmable signal processor*. A programmable signal processor may use a thousand integrated circuits, with each integrated circuit equivalent to a thousand discrete transistors. Although an integrated circuit costs no more than a few tens of dollars, it is evident that the programmable signal processor increases the cost of the radar by (the order of) a hundred thousand dollars. For this, a good basic radar becomes the equivalent of a half dozen special purpose radars.

The coherent transmitter which underlies this evolution towards improved flexibility and versatility is a high vacuum thermionic device. In the future, solid-state transmitters will begin to replace the tubes in current use. The benefits will include improved reliability[1] because all current transmitter types require one or more high voltage power supply/modulators, comparatively complex cooling provisions, and substantial allocations of space. High voltage generation and waste heat removal are always sources of unreliability, and hence some gains in radar performance can be expected from the introduction of the solid-state transmitter. The solid-state transmitter is based on the use of a multiplicity of negative resistance diodes. These are intrinsically simple devices so that the complete solid-state transmitter can be considered an ensemble of many identical and simple circuits. Of all the performance innovations foreseen for future radars, the solid-state transmitter may prove to be one of the few to reduce cost.

Coded pulses will generally be used with solid-state transmitters since the peak power of such is limited. The coding, or *pulse compression* circuitry, allows for the generation and transmission of a long pulse which is compressed on reception using the information contained in the internal code. The basic benefit is that the average power of the

[1]However it should be noted that current generation transmitting tubes are not unreliable. For example, some traveling wave tubes last several thousand hours in operational radars, and the transmitters used in satellites, also traveling wave tubes, often last for four or five years of continuous operation.

transmission increases in direct proportion to the expanded pulse duration, whereas the range resolution (and the size of the clutter patch) is directly proportional to the duration of the compressed pulse. Ancillary benefits include increased covertness (the low peak power of the transmission makes the radar less visible to enemy intercept receivers) and increased resistance to jamming (the receiver converts uncoded and incorrectly coded jamming pulses to a noise-like waveform).

Electronic beam steering, extensively used in large ground- and sea-based radars but not yet widely employed in airborne radars because of weight and cost factors, will probably become a standard feature of the airborne fire control radars of the next decade. As proven in a few new radars (for example, the AUG-9 and APQ-140), the agile beam radar can continue the search function while tracking one or more targets. The new flexibility provided by the programmable signal processor can be better exploited with an agile beam antenna since the multiple modes of radar operation can be interlaced at rates of several tens to several hundreds of mode changes per second.

Given that newly designed radars are typically controlled by digital logic, the introduction of a *data bus* is inevitable. The combination of the controller, issuing queries and commands, and the data bus, relaying the information to the component parts of the radar, will eliminate almost all wiring between the major components of a radar. The exceptions, a few RF, IF, and critical video signals, will become ever fewer in number in future models of radars. The elimination of the monstrous "octopus" cables of presently operational radars will increase reliability and reduce weight.

The use of central digital controller and data bus implies subtle changes in *system organization*. These might not be immediately apparent on a system block diagram, but the design discipline inherent in these new systems tends to require *full interchangeability* of line replaceable units (LRUs). Many (perhaps most) LRUs in current radars can be replaced only at the cost of realigning the whole or a substantial part of the overall radar. Each of the fully interchangeable LRUs will cost a bit more, but a substantial saving will be made in the elimination of system alignment and test. A second use for a fully interchangeable LRU might be as a part of a completely different radar; this seems a reasonable goal which would result in savings since it would enlarge the production base.

In addition to these performance changes which have already been (at least partially) implemented, there are two additional technological changes which can be foreseen. One (already appearing in experimental hardware, i.e., Project SOTAS) is the evolution of the electronically scanned antenna to an *adaptive array*. The agile scanning feature of the antenna is retained in this mode of use but, in addition, the beam is distorted so that a deep null (very low sensitivity to incident waves) is developed in the direction of one or more jammers. In addition, the radar may be caused to dwell longer when looking in the direction of the jammer to enhance the probability of burn-through. The motivation, of course, is improved ECCM, and as frequently is the case, the cost of this feature is appreciable.

The other technological development is the DoD-sponsored effort in *very high speed/very large scale integrated circuits* (VHSIC/VLSIC). These devices promise to improve airborne fire control radars in several ways; among the hoped for improvements are more effective programmable signal processors, reduced size processors, and a more effective data bus. Astonishing predictions of the improvement in performance can be found in the literature, but the cost of these improvements (if realized) will be very high. The reasons are (1) the integrated circuits in current use are basically commercial devices where military purchases are only small add-ons to the civil demand and are made at the very low prices that result from volume production, whereas the converse situation will obtain (at least initially) with VHSIC/VLSICs; (2) the new technology will impose a new learning curve on the manufacturer; and (3) production volume will almost certainly be much lower than with present devices.

The performance improvements obtained in airborne radars over the twenty year period, 1960-1980, have substantially changed the functions expected of these systems. The basic function of the airborne fire control radar continues to be one of searching and tracking enemy aircraft; the new radars will perform many other important roles using techniques, procedures and devices that could not even be considered in 1960.

C. COSTS OF RADAR

We explored the feasibility of disentangling the cost implications of the two types of technological change which have affected radars. Unfortunately, quantitative data similar to those available for airframes could not be obtained for the radars. We therefore relied on a qualitative, Delphi-like analysis.

Conversations with a small number of highly knowledgeable managers and analysts suggested that significant improvements in manufacturing efficiency have been made over the past two decades, but these cost reductions have been small relative to cost increases resulting from improving radar performance.

Moreover, it is extremely difficult to disentangle the two types of technological change. Many of the factors which contributed to improved manufacturing efficiency also enhanced performance. Thus a single integrated circuit may contain several thousand transistors and their associated passive components. A radar of the early 1960s would not even contain that many discrete transistors and tubes. Since a modern radar will typically contain far more than a thousand integrated circuits, it is obvious that the two types of change are related. However, the best estimate of the experts indicates that a radar with 1960 performance specifications built with current methods and techniques would cost 10 to 40 percent less in real terms than it cost in 1960. The median estimate of the cost saving was 20 percent.

It was not possible to obtain estimates which measured the effects of each of the increases in performance requirements.

D. SUMMARY

We have observed two kinds of technological changes in airborne fire control radars. These were the same factors which were discovered for airframes, i.e., manufacturing technique and product quality changes. We conclude, as we did above, that increases in costs attributable to increased performance requirements exceeded the savings accruing from greater productivity in the manufacturing process.